AUGUST 2024

M.Sc. in Civil Engineering

ZEHRA SAKINÇ

REPUBLIC OF TÜRKİYE
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

WATER, CARBON and ENERGY FOOTPRINT of PLASTERBOARD PRODUCTION

M.Sc. THESIS
IN
CIVIL ENGINEERING

BY
ZEHRA SAKINÇ
AUGUST 2024

WATER, CARBON and ENERGY FOOTPRINT of PLASTERBOARD PRODUCTION

M.Sc. Thesis

in

Civil Engineering

Gaziantep University

Supervisor

Prof. Dr. Mehmet İshak YÜCE

Co-Supervisor

Assoc. Prof. Dr. Abdullah MURATOĞLU

by

Zehra SAKINÇ

August 2024

WATER, CARBON, and ENERGY FOOTPRINT of PLASTERBOARD PRODUCTION

submitted by **Zehra SAKINÇ** in partial fulfillment of the requirements for the degree of Master of Science in **Civil Engineering Department, Gaziantep University** is approved by,

Prof. Dr. Çiğdem AYKAÇ
Director of the Graduate School of Natural and Applied Sciences ………..............

Prof. Dr. Nildem TAYŞİ
Head of the Department of Civil Engineering ………..............

Prof. Dr. Mehmet İshak YÜCE
Supervisor, Civil Engineering
Gaziantep University ………..............

Assoc. Prof. Dr. Abdullah MURATOĞLU
Co-Supervisor, Civil Engineering
Batman University ………..............

Exam Date: 26 August 2024

Examining Committee Members:

Prof. Dr. Mehmet İshak YÜCE
Gaziantep University ………..............

Prof. Dr. Ali AYTEK
Gaziantep Islam Science and Technology University ………..............

Asst. Prof. Dr. Gökmen ÖZTÜRKMEN
Gaziantep University ………..............

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Zehra SAKINÇ

ABSTRACT

WATER, CARBON and ENERGY FOOTPRINT of PLASTERBOARD PRODUCTION

SAKINÇ, Zehra
M.Sc. in Civil Engineering
Supervisor: Prof. Dr. Mehmet İshak YÜCE
Co-Supervisor: Doc. Dr. Abdullah MURATOĞLU

August 2024

72 pages

This thesis comprehensively analyzes the environmental impacts associated with the production of gypsum plasterboards, which are widely used in the construction industry. The study focuses on the water, carbon, and energy footprints, aims to examine the resource consumption and emissions released throughout the production processes, from raw material extraction to the final product. The water footprint (WF) was calculated using the chain-summation approach of 'Water Footprint Assessment Manual' as a reference. The carbon footprint (CF) assessment was conducted based on IPCC guidelines and the energy footprint (EF) was determined to quantify the total energy consumed during the production processes. The analysis revealed that the production of gypsum plasterboard has an average 28.45 l/m^2 WF which is mostly associated to the indirect consumption during the production stage. The CF of 1 m^2 of plasterboard is calculated to be approximately 1.463 kg CO_2 equivalent, primarily due to the use of natural gas in dryers and electricity consumption during various production stages. The EF is obtained to be 23.586 MJ/m^2. This study provides crucial insights for enhancing sustainability in gypsum plasterboard production and establishes a foundation for future research in similar industries.

Key Words: Gypsum, Plasterboard, Water Footprint, Carbon Footprint, Energy Footprint

ÖZET

ALÇI PLAKA ÜRETİMİNİN SU, KARBON VE ENERJİ AYAK İZİ

SAKINÇ, Zehra
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Mehmet İshak YÜCE
İkinci Danışman: Doç. Dr. Abdullah MURATOĞLU

Ağustos 2024

72 sayfa

Bu tez, İnşaat sektöründe yaygın olarak kullanılan alçı levha üretimi ile ilişkili çevresel etkilerini kapsamlı bir şekilde analiz etmektedir. Çalışma su, karbon ve enerji ayak izlerine odaklanarak, hammaddelerin çıkarılmasından nihai ürüne kadar olan üretim süreçlerindeki kaynak tüketimini ve salınan emisyonların ayrıntılı bir şekilde incelemeyi amaçlamaktadır. Su ayak izi (SA), 'Su Ayak İzi Değerlendirme El Kitabı'nın Zincir Toplam yöntemi uygulanarak hesaplanmıştır. Karbon ayak izi (KA) değerlendirmesi, IPCC yönergelerine dayanarak yapılmıştır ve enerji ayak izi (EA), üretim süreçleri boyunca tüketilen toplam enerjiyi belirlemek amacıyla belirlenmiştir. Analiz sonuçları, alçı plaka üretiminin ortalama 28,45 l/m^2 SA ’ne sahip olduğunu ve bunun çoğunlukla üretim aşamasındaki dolaylı tüketimle ilişkili olduğunu ortaya koymuştur. 1 m^2 alçı plakanın karbon ayak izi, yaklaşık 1,463 kg CO_2 eşdeğeri olup, bu emisyonların başlıca kaynakları arasında fırınlarında doğal gaz kullanımı ve çeşitli üretim aşamalarında elektrik tüketimi yer almaktadır. EA ise 23,586 MJ/m^2 olarak elde edilmiştir. Bu çalışma, alçı plaka üretiminde sürdürülebilirliğin artırılmasına yönelik önemli bilgiler sağlamaktadır ve bu alandaki gelecekteki araştırmalar için bir temel oluşturmaktadır.

Anahtar Kelimeler: Alçı, Alçı Levha, Su Ayak İzi, Karbon Ayak İzi, Enerji Ayak İzi

''Dedicated to my family''

ACKNOWLEDGEMENTS

I would like to extend my sincere gratitude to my supervisor, Prof. Dr. Mehmet İshak YÜCE, for his invaluable guidance and support throughout the study. I am thankful for his encouragement and motivation.

I am also deeply grateful to my Co-Supervisor, Assoc. Prof. Dr. Abdullah MURATOĞLU, for his continuous support and insightful feedback. His dedication and enthusiasm have significantly contributed to the depth and quality of this work, and I am profoundly appreciative of his expert guidance and invaluable suggestions.

I would also like to extend my heartfelt thanks to my beloved family my father Nimet SAKINÇ, my mother Fatime SAKINÇ, and my siblings. Their unwavering support and constant encouragement have been a source of great strength throughout the writing of this thesis. I am profoundly grateful for their presence and dedication.

Additionally, I would like to express my deepest gratitude to my coworkers for their unwavering support and encouragement throughout the duration of this thesis. Their understanding, helpfulness, and willingness to share knowledge have been a great source of inspiration for me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OFABBREVIATIONS

CBDR-RC	Common but Differentiated Responsibilities and Respective Capabilities
CF	Carbon Footprint
CFCs	Chlorofluorocarbons
CH_4	Methane
COP7	7th Conference of the Parties
COP21	the 21st Conference of the Parties
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equal Greenhouse Gases
EF	Energy Footprint
ET	Employee Transportation
FGD	Flue Gas Desulfurization
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
NCV	Net Calorific value
N_2O	Nitrous Oxide
OECD	Organization for Economic Co-Operation and Development
PGP	Powder Gypsum Plant
PP	Plasterboard Plant
RME	Raw Material Extraction
RMT	Raw material Transportation
SF_6	Sulfur Hexafluoride
UNFCCC	United Nations Framework Convention on Climate Change
WF	Water Footprint

CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

One of the greatest challenges of the 21st century is the rapid population growth, which has led to a consequent increase in industrialization, urbanization, and the rise in production and consumption to meet human needs. The global population has been growing at an unprecedented rate, reaching approximately 7.8 billion in 2020 and projected to exceed 9.7 billion by 2050 [1]. This exponential population growth has significantly intensified the demand for resources, leading to extensive urban development and industrial expansion.

As cities expand to accommodate the growing population, urban areas are increasingly consuming land, water, and energy at an accelerated rate. The process of urbanization is often accompanied by increased industrial activities, which are essential for the production of goods and services required by the people. However, this industrial growth comes with its own set of challenges, including increased greenhouse gas emissions, resource depletion, and environmental degradation.

One of our most critical resources at risk of depletion due to increasing population, rising living standards, and industrialization is water. Approximately two-thirds of the global population, around 4 billion people, experience severe water scarcity for at least one month each year, with half a billion facing it year-round [2]. Water is an essential requirement for all sectors. However, the amount of water that is supplied to the human consumption is quite limited on earth. Accordingly, efficient and optimal management of available water resources in each sector is becoming increasingly important. One of the important tools for managing water resources is the water footprint (WF). WF was initially introduced by Hoekstra in 2002 as a consumption-based measure of water utilization. It is a multi-dimensional indicator that shows the volume of water consumed by source and the volume of water polluted by type of pollution [3].

Another resource that is being depleted with the increasing population and the Industrial Revolution is energy. The rise in energy consumption has led to both the risk of depleting energy resources and the increase in greenhouse gas emissions caused by energy use in the atmosphere. Greenhouse gases prevent solar radiation from being reflected back into space, resulting in a rise in Earth's temperature. Consequently, global warming and climate change have emerged as pressing issues with visible impacts that cannot be ignored. To mitigate the rate of climate change, it is crucial to identify the contributing factors and assess their impact levels, implementing appropriate preventive measures. A vital tool in this effort is the calculation of the carbon footprint (CF), which has recently gained widespread use and popularity for measuring greenhouse gas emissions.

Given that non-renewable resources are limited and reserves are depleting, the efficient use of energy has become another crucial issue. One of the important tools for effectively managing the increasing energy demand and mitigating the environmental impacts of energy usage associated to the population growth and industrialization is the energy footprint (EF). EF analysis is the evaluation of energy consumption procedures from a life cycle perspective in relation to a defined product, organization or region within a specific spatial and temporal boundary. EF studies aim to optimize energy usage in order to ensure a sustainable future for upcoming generations.

The construction industry is a significant contributor to environmental impacts due to its extensive use of natural resources, high energy consumption, as well as its emissions of greenhouse gases. In 2018, the buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related emissions; therefore, it should be a primary target for GHG emissions mitigation efforts [4]. The construction industry's high energy use and large material demands make it a key focus for sustainability efforts. Adopting more sustainable practices in this sector is essential for meeting international climate goals and lowering its environmental impact.

Among the materials used in this industry, gypsum and gypsum plasterboard stands out for its versatility and widespread application in both residential and commercial buildings. Gypsum is widely used in the production of plasterboard due to its fire-resistant properties and ease of application, making it a preferred choice for interior walls and ceilings. As the construction sector continues to grow, the demand for gypsum plasterboard has significantly increased, highlighting the importance of examining its environmental impacts. Understanding these impacts is essential for developing sustainable building practices and reducing the construction industry's overall footprint. As sustainability becomes an increasingly critical focus, understanding the environmental impacts of gypsum plasterboard production is essential.

In this thesis, water, carbon, and energy footprint calculations have been conducted to evaluate the environmental impacts of gypsum plasterboard production, which is widely used in the construction sector. The study covers all processes from cradle to factory gate, including raw material extraction and grinding, powder gypsum production, and gypsum plasterboard production. Powder gypsum and gypsum plasterboard production facility located in Türkiye was selected as the study area. The company's name has not been disclosed to protect its interests and maintain its competitive advantage. All data were provided by the company. For WF calculations, the 'Water Footprint Assessment Manual' and the 'chain summation approach' were utilized. CF calculations were based on IPCC guidelines. Since there is no specific standard for energy footprint calculations, the study ‘Re-defining and conceptualizing the Energy Footprint as a Standalone Indicator’ by Muratoğlu was referenced [5].

Sustainability in construction industry involves reducing the consumption of water and energy, minimizing carbon emissions, and optimizing production processes. This thesis aims to clarify the environmental impacts associated with gypsum plasterboard production through detailed footprint analyses. Such insights are vital for developing strategies to mitigate environmental impacts, thereby contributing to the broader goals of sustainable development in the construction industry.

Furthermore, this thesis seeks to fill the gaps in existing research by providing a holistic analysis of the water, carbon, and energy footprints specific to gypsum plasterboard production. This comprehensive approach not only enhances our understanding of the environmental burdens of plasterboard but also identifies opportunities for improvements and innovations in production practices. The findings of this study can serve as a valuable resource for industry stakeholders, policymakers, and researchers working towards a more sustainable construction sector.

1.2 Objectives of the Thesis

The objectives of this thesis are to:

- Conduct a comprehensive analysis of the WF of gypsum plasterboard production, employing detailed data from each stage of the production processes. This includes quantifying water usage and understanding the specific contributions of various processes to the overall WF.
- Evaluate the CF of gypsum plasterboard production, taking into account both direct and indirect emissions throughout the production lifecycle. This involves assessing emissions from raw material extraction, transportation, manufacturing, and other related activities.
- Assess the EF of the production processes, identifying key areas of energy consumption and potential efficiencies.
- Compare the environmental impacts of gypsum plasterboard production with those reported in existing literature, and suggest improvements based on the findings.

1.3 Structures of the Thesis

This thesis is organized into five chapters as follows:

Chapter 1: Introduction - This chapter introduces the background and motivation for the study, outlining the significance of understanding the environmental impacts of gypsum plasterboard production. It sets forth the research objectives, the scope of the study, and provides an overview of the thesis structure to guide the reader through the subsequent chapters.

Chapter 2: Literature Review - This chapter provides a detailed review of the theoretical background relevant to the study. It covers sustainability challenges in the construction industry, the explanation of impacts and significance of climate change, a detailed analysis of greenhouse gases and their effects, and important historical protocols for climate change. Furthermore, it reviews previous studies on the environmental impacts of gypsum and plasterboard production, highlighting key findings, methodologies, and gaps in the current knowledge that this thesis aims to address.

Chapter 3: Material and Method - This chapter describes the various types of gypsum and their specific functions in plasterboard production. It introduces the study factory, detailing its production processes. The chapter elaborates on the methodologies used for analyzing the water, carbon, and energy footprints, including analytical tools, and calculation methods.

Chapter 4: Results - Presents the findings from the footprint analyses, including detailed data and calculations for the years 2021, 2022, and 2023. It includes comprehensive tables, graphs, and charts to illustrate the water, carbon, and energy footprints of the production processes.

Chapter 5: Discussion - This chapter compares the findings of this thesis with previous studies, and provides recommendations for future research and improvements in the production processes.

Chapter 6: Conclusion

CHAPTER 2
LITERATURE REVIEW

2.1 Theoretical Background

2.1.1 Sustainability Challenges (Problem definition)

The rapid increase in the human population has led to an exponential growth in the demand for basic human necessities, including water, energy, and food. The heightened demand for these resources has led to a corresponding increase in the consumption of fossil fuels, which, in turn, results in the emission of greenhouse gases that adversely affect ecosystems. These environmental challenges have amplified interest in sustainability research and problem-solving studies aimed at enhancing social, economic, and human well-being. The focus on sustainable practices is crucial for mitigating the negative impacts of increased resource consumption and for developing innovative solutions that promote long-term ecological balance and human prosperity.

2.1.2 Climate change

A clear understanding of the term "climate" is necessary to fully comprehend the concept of climate change. According to the Ministry of Environment and Urbanization, Directorate of Climate Change, climate is defined as the average state of weather conditions experienced or observed over many years in any location on Earth. More systematically, it is described as the synthesis of long-term statistics of atmospheric elements' variability and average values in a specific area [6].

According to the Intergovernmental Panel on Climate Change (IPCC), climate change refers to natural or human-induced changes in the fundamental characteristics of the climate system, such as temperature and precipitation, that can be detected through statistical analysis over a long period (typically ten years or more) [7]. The emphasis on human influence in the IPCC's definition generally highlights the connection between human activities and climate change. The primary drivers of climate change are predominantly anthropogenic. These include a wide range of activities, such as the burning of fossil fuels, deforestation, and industrial processes that release large amounts of greenhouse gases into the atmosphere. The combustion of fossil fuels, such as coal, oil, and natural gas, for energy and transportation, is the largest source of CO_2 emissions. Deforestation for agricultural expansion, urban development, and logging reduces the number of trees that can absorb CO_2 from the atmosphere, exacerbating the greenhouse effect.

At this point, a key concept associated with climate change, known as global warming, becomes relevant. Global warming refers to the increase in Earth's average temperature due to human activities like burning fossil fuels and deforestation. These actions release greenhouse gases, such as carbon dioxide and methane, which trap heat by absorbing thermal radiation from the Earth's surface, preventing it from escaping back into space. This enhanced greenhouse effect leads to a warming of the Earth's surface [8].

Climate change is a consequence of global warming, and both phenomena have various negative outcomes. The impacts of climate change are extensive and affect many aspects of the environment and human society. These effects include rising global temperatures, changing precipitation patterns, and increasing sea levels. The rise in global temperatures affects ecosystems and weather patterns, leading to more frequent and severe weather events such as heatwaves, storms, and hurricanes. Changes in precipitation patterns can cause droughts in some regions and floods in others, disrupting agricultural productivity and water supply. The melting of polar ice caps and glaciers, combined with the thermal expansion of seawater, results in rising sea levels, posing significant threats to coastal communities, infrastructure, and ecosystems. [9].

2.1.3 Greenhouse Gases

Greenhouse gases are primarily produced from the burning of fossil fuels, such as coal, oil, and natural gas, and they contribute significantly to global climate change and global warming. According to the reports of the IPCC, the primary greenhouse gases are identified as Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Chlorofluorocarbons (CFCs), Hydrofluorocarbons (HFCs), and Sulfur Hexafluoride (SF6). Each of these gases plays a distinct role in the greenhouse effect and varies in its impact on global warming. Carbon dioxide makes the most significant contribution to greenhouse gases resulting from human activities. Therefore, greenhouse gases are often expressed in terms of CO_2 equivalent [10].

2.1.3.1 Carbon Dioxide

Carbon dioxide (CO_2) is the most significant greenhouse gas in terms of its contribution to the greenhouse effect. While a small amount is released through natural processes such as respiration and decomposition, the majority of CO_2 emissions are due to anthropogenic activities, including fossil fuel combustion and deforestation[11]. Before the industrial revolution, the atmospheric CO_2 concentration was approximately 280 ppm. However, extensive industrial activities have significantly increased this concentration, reaching about 419 ppm by 2023 [12]. This increase in CO_2 levels is primarily due to the burning of fossil fuels for energy, industrial processes, and large-scale deforestation, which reduces the number of trees that can absorb CO_2.

2.1.3.2 Methane

Among greenhouse gases, methane (CH_4) is the second most significant contributor to global warming. Methane is a potent greenhouse gas with a global warming potential approximately 28 times greater than that of CO_2 over a 100-year period [13]. It is primarily produced from anaerobic decomposition in wetlands, agriculture (especially rice paddies), livestock digestion, and fossil fuel extraction and distribution. Despite its lower concentration in the atmosphere compared to CO_2, methane accounts for about 20% of the enhanced greenhouse effect due to its high efficiency in trapping heat [14].

2.1.3.3 Nitrous Oxide

N_2O is another critical greenhouse gas with a significant global warming potential, approximately 265 times that of CO_2 over a 100-year period.[13] Nitrous oxide holds a significant position among nitrogen oxides. It is estimated that this gas is responsible for approximately 15% of the greenhouse effect. It can remain in the atmosphere for up to 120 years and has a high heat-trapping potential [15]. It is released mainly through agricultural practices, including the use of synthetic and organic fertilizers, fossil fuel combustion, and various industrial processes [16].

2.1.3.4 Sulfur Hexafluoride

Sulfur Hexafluoride (SF_6) is a colorless, odorless, and non-flammable greenhouse gas known for its high dielectric strength. Due to its exceptional electrical and chemical stability, along with its ability to absorb heat and extinguish arcs, SF_6 is extensively utilized in various fields, particularly in the electrical industry [17]. Despite its low concentrations, SF_6 gas has a high global warming potential [15].

2.1.3.5 Chlorofluorocarbons and Hydrofluorocarbons

CFCs (Chlorofluorocarbons) and HFCs (Hydrofluorocarbons) are greenhouse gases that do not occur naturally but are used in various industrial applications due to their unique properties. These gases contribute to the depletion of ozone concentration in the stratosphere by preventing the reformation of ozone molecules, leading to the thinning of the ozone layer [18]. CFCs, known for their heat absorption capacity, are non-toxic, non-flammable, and chemically stable. These characteristics make them widely used in air conditioning systems. Besides their application in climate control systems, CFCs are also used as insulation materials, in rigid and flexible foam products, in aerosols in spray cans, and in the defense industry. The emissions from these applications are purely anthropogenic [14].

2.1.4 Climate Change Protocols

To mitigate climate change and reduce greenhouse gas emissions, several agreements and protocols have been signed. The most significant among these are the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Paris Agreement.

UNFCCC established with the goal of "stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system," was extensively negotiated in intergovernmental conferences during the late 1980s. It was opened for signature at the Earth Summit in Rio de Janeiro in 1992 and entered into force on March 21, 1994 [19].

The UNFCCC is based on the principle of "Common but Differentiated Responsibilities and Respective Capabilities" (CBDR-RC), which recognizes that while all countries are responsible for addressing climate change, they have different capabilities and levels of responsibility. The Convention categorizes countries into

Annex I, Annex II, and non-Annex I groups. Annex I include industrialized countries and economies in transition, which are required to take the lead in reducing greenhouse gas emissions. Annex II comprises a subset of Annex I countries that are additionally obliged to provide financial and technological support to developing countries. Non-Annex I countries, primarily consisting of developing nations, are encouraged to contribute to the global effort according to their capabilities and specific national circumstances [19], [20].

As of now, 197 countries have ratified the UNFCCC. Türkiye became a Party to the Convention on May 24, 2004, after the ratification through Law No. 4990 published in the Official Gazette on October 21, 2003. Initially included in both Annex I and Annex II due to its status as a founding member of the Organization for Economic Co-Operation and Development (OECD), Türkiye's unique position was recognized during the 7th Conference of the Parties (COP7) in Marrakesh in 2001. Consequently, Türkiye was removed from Annex II but remained in Annex I, acknowledging its distinctive circumstances compared to other Annex I countries [19].

The Kyoto Protocol, adopted on December 11, 1997, and coming into force on February 16, 2005, is an international treaty that operationalizes the UNFCCC by committing its Parties to internationally binding emission reduction targets. This protocol specifically targets industrialized countries and economies in transition, recognizing their significant responsibility for the current high levels of greenhouse gas (GHG) emissions due to over a century of industrial activities. As of now, the Kyoto Protocol has 192 Parties, illustrating a broad international consensus on the need to address climate change through collaborative efforts [21].

The Paris Agreement, adopted on December 12, 2015, during the 21st Conference of the Parties (COP21) in Paris, France, is a legally binding international treaty on climate change that entered into force on November 4, 2016. Approved by 196 Parties, its main objective is to limit the global average temperature increase to well below 2°C above pre-industrial levels, with further efforts to restrict the rise to 1.5°C. This goal is critical to preventing severe climate impacts such as frequent droughts and heatwaves. The Agreement requires countries to submit increasingly ambitious climate action plans known as nationally determined contributions every five years and provides a framework for financial, technical, and capacity-building support to developing nations, ensuring transparency and accountability through a global stock take mechanism [22].

Another important policy related to climate change is the European Green Deal, adopted by the European Union in December 2019. This policy aims to make Europe the first climate-neutral continent by 2050. It provides a comprehensive roadmap, including measures such as reducing greenhouse gas emissions, investing in renewable energy, promoting energy efficiency, and fostering sustainable industry and agriculture. The Green Deal also emphasizes decoupling economic growth from resource use, aiming for a just and inclusive transition that leaves no one behind [23].

2.2 Previous studies

Up until now, several evaluations of the environmental impact of gypsum production have been carried out. Majority of the literature studies on carbon, energy and water footprint of gypsum and its sub–products are based on life cycle analysis. The author has not found any study of gypsum and its products that comprehensively analyzed the water, carbon and energy footprint.

Fort and Cerný [24] analyzed the carbon footprint of calcined gypsum production. They analyzed two types of gypsum: natural gypsum and flue gas desulfurization (FGD) gypsum according to the standard of ISO 14067. Data gathered from direct material producers. For both raw materials, calcination is identified as the most harmful process in terms of carbon dioxide production. For the production of natural gypsum, mining has the second most significant environmental impact. This process generates approximately 15% of greenhouse gas emissions. On the other hand, the dewatering of flue gas desulphurization gypsum, separating it from other residuals, ranks as the second most important contributor to greenhouse gas effects. The results of the environmental assessment showed that 140.2 kg CO_2/tons of carbon dioxide was produced for natural gypsum and 105.3 kg CO_2/tons of carbon dioxide for FGD gypsum.

Giama and Papadopoulos [25] analyzed the environmental impacts resulting from the analysis of the environmental performance of the most commonly used building materials such as; concrete, plaster and brick elements. They used Life Cycle Analysis (LCA) and Carbon Footprint Analysis methodologies. They underline that production and transport were the two processes most responsible for CO_2 emissions. In the context LCA, greenhouse gas emissions were quantified using SimaPro software, revealing values of 0.22191 t GHG/kg for cement plaster, 0.39226 t GHG /kg for plasterboard, and 0.2619 t GHG /kg for common plaster. In parallel, Carbon Footprint analysis yielded the following results: 0.002124 t CO_2eq /kg for cement, 0.0001 t CO_{2eq} /kg for plasterboard, and 0.000778 t CO_{2eq} /kg for concrete plaster.

Schlegel and Shtiza [26] conducted a study on the comparative environmental footprint of masonry mortar, lime-cement plasters, and gypsum plaster formulations. They follow ISO 14044-4 standards. They used European Reference Life Cycle Database for gypsum plaster. The average energy consumption of a gypsum-based plaster is calculated to be 3540 MJ/t and the global warming potential (GWP) is calculated to be 202 kg CO_{2eq} /t. When comparing lime-based and gypsum-based plasters, gypsum-based plasters have a lower environmental footprint, and if long-term carbonization is not taken into account, lime-based mortars have a higher carbon footprint and therefore a higher GWP.

Lushnikova and Dvorkin [27] investigated the sustainability of gypsum products as a construction material. The study estimated the carbon footprint value and embodied energy of gypsum plaster, which exhibits an embodied energy of approximately 1.8 MJ/kg and a carbon footprint of about 0.12 kg CO_2 per 1 kg. In the case of gypsum plasterboard, the embodied energy is noted to be 6.75 MJ/kg, accompanied by a carbon footprint of 0.38 kg CO_2 per 1 kg Life cycle assessments of gypsum products are conducted from cradle to gate, adhering to ISO 14025 and 21930 standards. According to the life cycle assessment results, when considering a 1000 sq ft area of gypsum plasterboard with a thickness of 5/8'', the global warming potential is calculated to be 317.4 kg CO_2 equivalent.

The Athena Sustainable Materials Institute published a comprehensive report analyzing the cradle-to-gate life cycle assessment (LCA) of Type X conventional gypsum board and lightweight gypsum board, produced by Gypsum Association members in the United States and Canada. The 2017 study collected life cycle inventory (LCI) data for three primary gate-to-gate processes involved in plasterboard production: the extraction of natural or raw gypsum ore, the production of gypsum face and backing paper, and the manufacturing of plasterboard. The LCA model was developed using SimaPro v.9.0.0.30 (2020) and was conducted in accordance with ISO 14040/44 standards and the requirements of ISO 21930:2017. The findings indicate that the production of 92.9 square meters of 15.9 mm (1 MSF 5/8") Type X conventional plasterboard results in the emission of 277 kg of CO2 equivalent greenhouse gases and requires approximately 4.3 GJ of primary energy. Furthermore, the cradle-to-gate production of 92.9 square meters of 12.7 mm (1/2" 1 MSF) lightweight gypsum board involves approximately 3.2 GJ of primary energy and emits 207 kg of CO2 equivalent greenhouse gases [28].

Venta et al. [29] conducted a cradle-to-gate life cycle inventory analysis regarding gypsum board and its associated finishing products. According to the report the average energy consumption (diesel-road, coal, oil, electric) of ½ inch thick regular gypsum board is as follows: the extraction of gypsum consumes an average of 0.3546 MJ/m^2 of energy, the transport of gypsum consumes 4.6686 MJ/m^2 and the transport of paper consumes an average of 0.3587 MJ/m^2 of energy in Canada. The weighted average energy consumption during the production of gypsum board has been estimated as 35.5387 MJ/m^2. Of the overall energy utilized, 19.66% is expended on paper manufacturing, 29.96% for stucco manufacturing, and 50.38% for the manufacturing of board. Atmospheric emissions from the calcination of stucco, the production of paper, and the manufacturing of boards amount to 976 G/m^2 of CO_2, 3.3985 G/m^2 of SO_2, 1.4518 G/m^2 of NO_X, 0.0281 G/m^2 of VOC, 0.0210 G/m^2 of CH_4, and 0.2625 G/m^2 of CO.

Life cycle assessment of glass mat gypsum panels was reported by the Athena Sustainable Materials Institute for the USA and Canada for the reference year 2013 according to ISO 14025:2006, ISO 21930:2007 and EN 15804:2012. For the cradle-to-gate model SimaPro LCA software 8.1.0.60 was used. Electricity and natural gas were identified as the primary sources of energy used in manufacturing. The study found that one thousand square feet of 1/2 inch thick glass mat gypsum wallboard consumes approximately 6.1 GJ of primary energy and emits 358 kg of greenhouse gases and non-renewable fossil fuels account for over 90% of primary energy supply. additionally, the 5/8 inch thick of the glass mat gypsum wallboard was found to emit 417 kg of greenhouse gases and require 7.1 GJ of primary energy. The main contributors to the total primary consumption of the plant were the on-site energy consumption and the use of fiberglass matting [30].

Rodrigo-Bravo et al. [31] conducted a life cycle analysis comparing standard gypsum ceiling tiles and polyurethane gypsum ceiling tiles. The research aimed to assess the environmental impact of the two materials and compared their environmental impacts. To accomplish this, the authors examined the extraction of raw materials, transportation, product use and stages for each type of tile. They use life cycle analysis methodology according to ISO 14040:2006 and ISO 14044:2006 standards. All data was obtained directly from producers, while secondary data for the years 2018 and 2019 was analyzed using SimaPro software. The analysis results revealed that the production stage has the most significant impact on the environment for both types of tiles compared to other stages. According to the article the polyurethane gypsum ceiling tile has better environmental performance this has been quantified as a 14% decrease in energy usage, a 14% decline in CO_2 emissions, and a 25% decrease in water usage compared to the standard tile.

Pedreño-Rojas et al. [32] investigate the environmental impact of producing natural and recycled gypsum in Spain. Life cycle analysis was carried out from the cradle to the gate using the Impact 2002+ methodology, and data directly from producers was analyzed for the LCA. Three scenarios were considered, the first being a reference scenario with natural gypsum production, the second with recycling of plasterboard waste and the third with recycling of gypsum powder waste. The findings indicate that recycled gypsum powder exhibits the minimum impact among all the examined categories. It demonstrates a reduction of 67.57% in comparison to plasterboard. The calcination phase is identified as the chief environmental impact in all scenarios. Notably, recycling gypsum can lead to savings of around 40-45% as compared to the production of natural gypsum.

Jimenez Rivero et al. [33] evaluated the energy and climate effects of varying degrees of plasterboard recycling. The life cycle model for gypsum plasterboard is formulated for the year 2013. It includes the extraction and processing of raw materials, manufacturing, use, and end of life. Scenario-based modelling is performed to assess the GHG and primary energy impacts of different levels of plasterboard recycling. They compare the actual situation in 2013 with two alternative scenarios: "Zero recycling case" (0% recycled gypsum) and "High recycling case" (18.7% reincorporated gypsum). They obtained that the impact of global warming, measured as CO_2 equivalents, is 2.53 kg CO_2eq/m^2 in the zero-recycling case, 2.45 kg CO_{2eq}/m^2 in the 2013 base case, and 2.23 kg CO_{2eq}/m^2 in the high recycling case. The analysis of greenhouse emissions reveals that the cradle-to-cradle lifecycle generates higher variations when transitioning from the base case of to the high recycling case. In the high recycling case, the total GHG emissions decrease by 9%.

Liu et al. [34] estimated the carbon, water and energy footprint of magnesium carbonate product using life cycle assessment method. The researchers aimed to assess current technological knowledge in the context of global sustainability goals and discussed to improve the life cycle environmental impact of a magnesium carbonate product with CO_2 capture and a mineralization process. Life cycle analyses were carried out employing the cradle to gate methodology in accordance with ISO 14040 and 14044 standards. Analyses were conducted for a total of 36 scenarios, investigating various OH/CO_2 replacement ratios, alkali sources and concentrated seawater sources. Based on the results, reducing the amount of alkali and water consumption is an effective strategy for process enhancement. Various scenarios using ammonia or waste alkali will reduce carbon dioxide and make the magnesium-based product to replace plasterboard with a negative carbon footprint. Regarding the energy footprint, a range of -2 MJ to 14 MJ for each kg of final product is observed in scenarios that use waste alkali with a 100% substitution rate.

Yaras et al. [35] conducted a study on the energy and carbon emission characteristics of gypsum wallboard with phase change material. This resulted in a total of four mixtures, comprising two reference and two composite gypsum mixtures. Various tests were performed to evaluate the effects of phase change materials on thermo-physical and mechanical properties, including a calculation of carbon emissions. According to the carbon emissions performance and energy savings analysis, the greatest carbon emissions reduction occurred with LPG (53.5 kg-CO_2/kWh) and fuel-oil (51.3 kg CO_2/kWh). By using composite gypsum wallboards of dimensions 3m*4m*0,2m, an energy saving of 15.95 kWh was achieved. The results indicate that increased use of phase change materials can lead to enhanced energy savings and reduced carbon emissions.

Buchanan and Honey [36] examined the energy use and related carbon dioxide emissions from building construction in New Zealand. They compared the energy and greenhouse gas emissions needed for various types of buildings, including houses, industrial structures, office buildings, and hostels. The energy analysis included both the direct process energy and the energy used for manufacturing and operating the necessary machinery and capital. Two scenarios were conducted to estimate carbon dioxide emissions: one with 75% of the electricity generated from hydropower, and the other with all electricity generated from fossil fuel power stations. The findings revealed that it takes 507 GJ of energy to construct a typical small house, measuring 94 m^2, over a 25-year lifespan. For an industrial building, the energy footprint is 3.2 GJ/m^2, with CO_2 emissions of 64.3 kg C/m^2 when using steel. However, using timber reduces the energy requirement to 1.8 GJ/m^2 and CO_2 emissions to 30.8 kg C/m^2. The production of building materials also releases about 400.000 tons of carbon, requiring 23 PJ of energy for manufacturing. Specifically, the production of gypsum plaster burns approximately 5765 MJ/m3 of fossil fuel energy and releases 115.5 C/m^3 of carbon.

Wang et al. [37] incorporated ground steel slag and a water retarding agent into calcined desulphurization gypsum to manufacture a sustainable gypsum with lower carbon emissions then they compared it with cement- and lime-based materials. The ideal plastering gypsum mixture comprised of 95% calcined desulphurization gypsum, 4.5% ground steel slag, and 0.5% water-retaining additive. The results of the life cycle analysis show that this gypsum mixture offers significant advantages over cement and lime-based products, resulting in lower energy consumption and lower emissions of carbon dioxide and Sulphur dioxide.

Maalouf et al. [38] conducted an objective evaluation of the energy and carbon footprint of using three eco-friendly construction materials for office façades in France and Italy. The authors used the simulation tool SPARK for a numerical assessment of thermal behavior, analyzing two conditions: constant and relative humidity-sensitive air flow rates. Emissions factors were taken from the Eco invent database to conduct life cycle assessments, following ISO 14040 and 14044 standards. SimaPro 8.0 software was used for estimating carbon footprint assessments. The analysis results state that the carbon footprint of Italia with constant air ventilation rate for hemp concrete is 186.07 $kgCO_{2eq}$. $kWh^{-1}y^{-1}$, for hemp concrete brick is 190.16 $kgCO_{2eq}$. $kWh^{-1}y^{-1}$ and for recycled polyethylene terephthalate is 184.52 $kgCO_{2eq}$. $kWh^{-1}y^{-1}$. Their results show that, compared to ventilation with a constant airflow rate, humidity-responsive ventilation reduces electricity consumption and it was revealed that the façade with the R-PET layer used less energy and emitted fewer greenhouse gases.

Papailiopoulou et al. [39] evaluated the impact of increasing the incorporation of recycled gypsum in plasterboard production on energy consumption. According to the results, the average impact on total energy consumption per square meter of plasterboard is practically insignificant, based on full-scale tests in five European plants. On average, there is a slight 0.1% increase in total energy, which is influenced by minor variations in thermal and electrical energy consumption. Certain process stages indicate a 1.5% rise in Stucco Production, while concurrently observing a 0.7% reduction in total energy consumption during the Plasterboard Production stage. The study showed that incorporating up to 30% recycled gypsum in plasterboard production has a negligible impact on total energy consumption, with the potential for significant energy savings through process optimization.

Emission amounts for some studies of similar materials with the method used are given in the table below.

Table 2.1 Previous studies emission values from the literature.

Reference	Material	Method	Software	Emission Amount
Fort and Cerný (2018)	Natural Gypsum	ISO 14067	-	140.2 kg CO_{2eq}/tons
	FGD Gypsum			105.3 kg CO_{2eq}/tons
Giama and Papadopoulos (2015)	Cement plaster	LCA (ISO14040-14044)	SimaPro	221.9 kg CO_{2eq}/tons
	Plasterboard			392.3 kg CO_{2eq}/tons
	Common plaster			261.9 kg CO_{2eq}/tons
Schlegel and Shtiza (2015)	Cement based mortar	LCA (ISO14040-14044)	-	180 kg CO_{2eq}/tons
	Lime based plaster			265 kg CO_{2eq}/tons

Lushnikova and Dvorkin (2016)	Gypsum based plaster	LCA (ISO14040-14044)	-	202 kg CO_{2eq}/tons
	Gypsum plaster			120 kg CO_{2eq}/tons
	Gypsum plasterboard			380 kg CO_{2eq}/tons
The Athena Sustainable Materials Institute (2020)	Gypsum plasterboard (5/8”)	LCA (ISO14040-14044)	SimaPro	277 kg $CO_{2eq}/92,9m^2$
	Lightweight Gypsum plasterboard (1/2”)			207 kg $CO_{2eq}/92,9m^2$
The Athena Sustainable Materials Institute (2016)	Glass mat gypsum panel (1/2”)	LCA (ISO 14025)	SimaPro	358 kg $CO_{2eq}/92,9m^2$
	Glass mat gypsum panel (5/8”)			417 kg $CO_{2eq}/92,9m^2$
Jimenez Rivero et al. (2016)	Plasterboard	LCA	-	2.53 kg CO_{2eq}/m^2
	High recycled plasterboard			2.23 kg CO_{2eq}/m^2
Liu et al. (2020	Mg based Material	LCA (ISO14040-14044)	-	150 kg CO_{2eq}/tons
Yaras et al. (2022)	Gypsum wallboard (LPG)	Carbon Emission Formula	-	53.5 kg CO_2/kWh
	Gypsum wallboard (Fuel oil)			51.3 kg CO_2/kWh
	Gypsum wallboard (Coal)			43.2 kg CO_2/kWh
	Gypsum wallboard (Natural gas)			42.1 kg CO_2/kWh
Maalouf et al. (2019)	Hemp-Concrete Brick	LCA (ISO14040-14044)	SimaPro	190.16 kg CO_2/kWh
	Hemp-Concrete			186.07 kg CO_2/kWh
	R-PET			184.52 kg CO_2/kWh

CHAPTER 3
MATERIAL AND METHOD

3.1 Gypsum and Gypsum plasterboard

Gypsum, a dihydrate form of calcium sulfate mineral, can be white, yellow, rose, or gray depending on its purity and form. Its usage dates back to ancient times, with the earliest known use at ÇatalHöyük, Türkiye around 6000 BC. This was followed by applications in the Egyptian pyramids between 2000-4000 BC. Gypsum plaster was also extensively used during the Roman and Renaissance periods. Although its usage declined during the Middle Ages, there was a revival of gypsum plaster in the 18th century in Portugal [40]. Today, gypsum and gypsum products continue to be widely used in various industries.

Gypsum mineral can be obtained in two ways by natural and synthetic processes. Natural gypsum (raw gypsum) is mined in rock form, formed as a result of complete or partial evaporation of inland seas or lakes. In nature it can be in different forms, the most common of which are calcium sulphate dihydrate ($CaSO_4.H_2O$) and anhydrate ($CaSO_4$) forms [41]. Synthetic gypsum has the same properties as natural gypsum and refers to a range of gypsum products resulting from industrial processing. The most common type of synthetic gypsum is flue gas desulphurization gypsum (FGD), which is obtained by removing Sulphur from flue gas to reduce Sulphur dioxide gas emissions in fossil fuel power plants. The use of synthetic gypsum offers advantages as it reduces environmental impact by utilizing waste material and preserves natural gypsum resources by reducing the need for mining [40].

Hemihydrate gypsum ($CaSO_4.1/2\ H_2O$) forms when gypsum loses three-quarters of its crystal water. Hemihydrate gypsum occurs in two forms: α-hemihydrate and β-hemihydrate. β-hemihydrate gypsum is produced through the partial dehydration of gypsum rock at temperatures between 130-150 °C in rotary kilns fired with coal, liquid fuel, or gas. This form is the gypsum plaster used in the building and construction industry. The α-hemihydrate gypsum is obtained by calcining gypsum in an autoclave using high-pressure steam. Calcination takes place in the presence of water and a small amount of organic matter [41]. α-gypsum is preferred in various industrial areas due to its high mechanical strength. High-quality α gypsum is used as mold plaster in dentistry, while lower strength α gypsum serves as ceramic mold plaster and is also used in sculpture and exterior decorations. Although these two forms are chemically identical, they differ in crystal structure. The crystal structure of β-hemihydrate gypsum is needle-like and amorphous, while that of α-hemihydrate gypsum is geometric [42].

The β-hemihydrate gypsum which is formed by crushing and grinding raw gypsum in mining areas, followed by drying in rotary furnaces is a powder that is commonly used in the construction sector. When mixed with water, gypsum powder forms a mortar-like consistency. This consistency allows for easy application to desired areas and dries to form a hard structure.

The TS EN 13279 standard covers the properties, performance, and conformity assessment of gypsum and gypsum binders in powder form in Türkiye. In accordance with this standard, gypsum plasters are classified as follows:

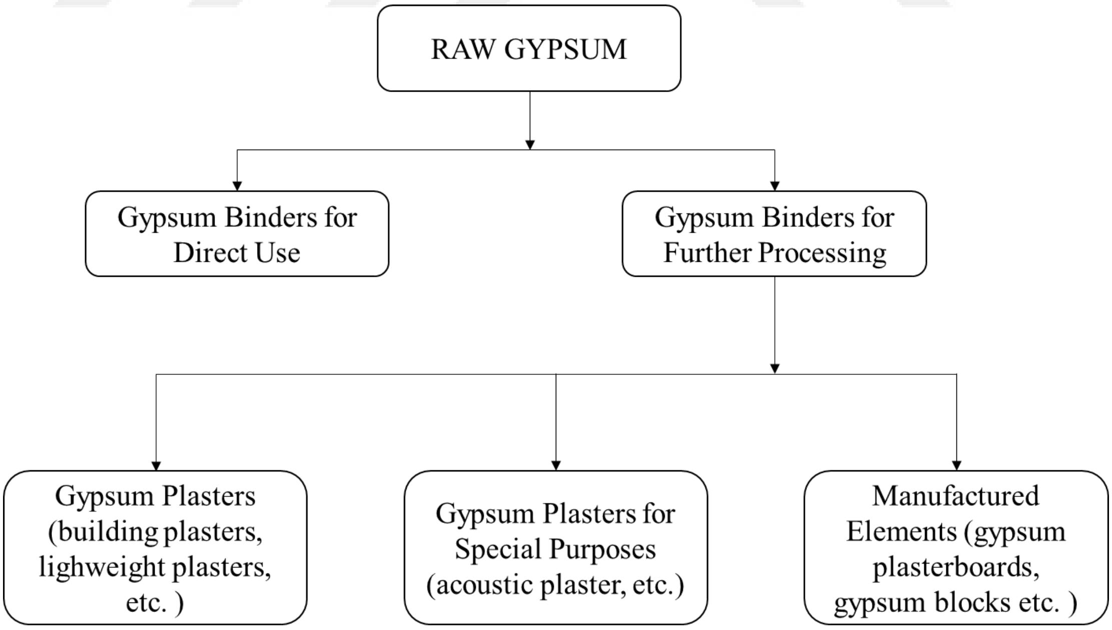

Figure 3.1 Classification of gypsum plasters according to TS EN 13279

Gypsum plasterboard is a rectangular gypsum product made by pouring a mortar of water, gypsum, and chemicals between two special papers and drying it in dryer. This composition of plasterboard helps it to gain features such as heat insulation, sound insulation and fire resistance. The standard that covers the properties, requirements, and test methods of gypsum plasterboard in Türkiye is the TS EN 520 standard. The table below presents the classification of gypsum plasterboard and ancillary products according to this standard.

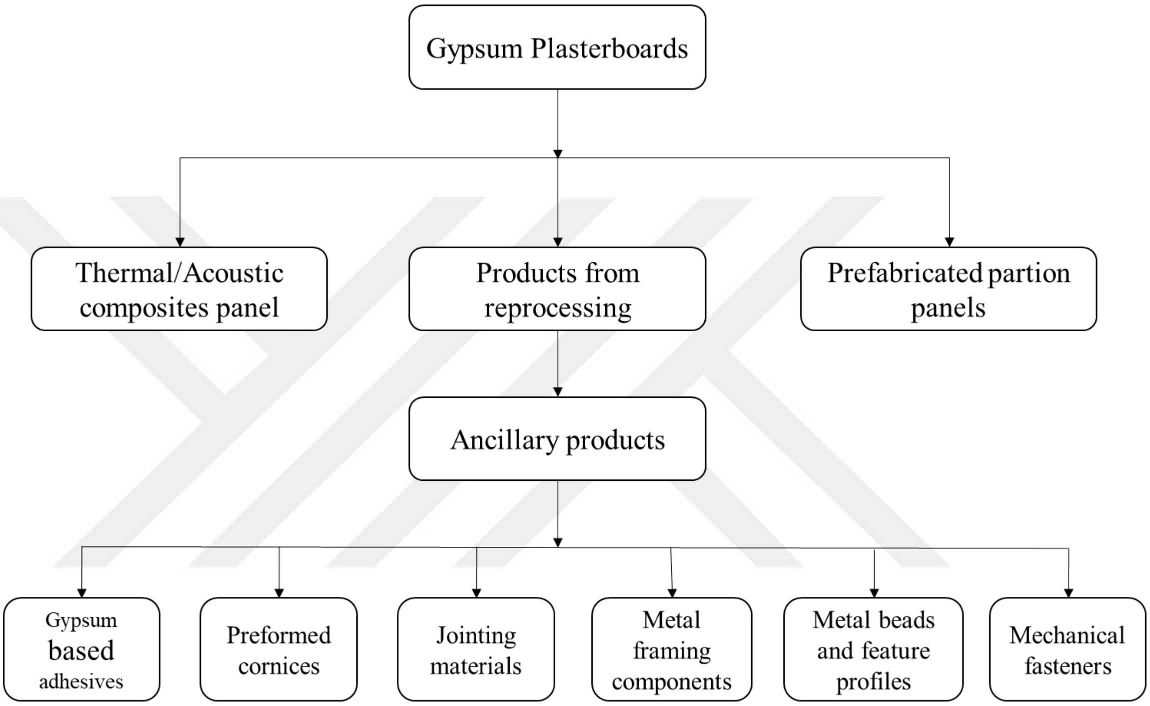

Figure 3.2 Classifications of gypsum plasterboards according to TS EN 520

3.2 Functions of Gypsum

The utilization of gypsum in the construction sector is advantageous in several respects. These include its ease of application, its capacity to regulate humidity, its lightness, its fire resistance, and its acoustic sound-balancing effect.

3.2.1 Ease of application

A key benefit of gypsum plaster in the construction industry is its ease of application. The powder form of gypsum, which is produced by evaporating the crystalline water within the gypsum stone, is mixed with water at the construction site and takes on the consistency of mortar. This mortar can then be applied to the desired location with relative ease, and it will subsequently dry and regain its hard stone form. The application of plaster in a mortar consistency to a variety of challenging surfaces is a relatively straightforward process. Chemicals are employed to determine the setting time of the gypsum plaster following its application to the wall. The use of these chemicals allows for the setting time to be adjusted, thus facilitating the shaping of the application and enhancing the ease of use.

The volume of gypsum plaster mortar expands at the beginning of hardening, but this rate is very small. Therefore, no significant change in its dimensions is observed after drying. This results in a series of advantageous characteristics of molded gypsum products, including a smooth surface, an accurate measurement, distinct and plump edges and corners [43]. This means it does not shrink and crack like concrete, and it does not change size or shape even when it absorbs moisture like wood.

3.2.2 Capacity to regulate humidity

The porous structure of plaster enables it to absorb vapor from the air and regulate the humidity level of indoor air. Its high porosity and uniform pore size distribution facilitate favorable permeability, making it a suitable material for humidity control applications [43], [44]. It is capable of absorbing additional moisture from the air when it is humid and releasing it when the air is dry, thereby maintaining a comfortable environment within the room [40].

3.2.3 Lightness

Gypsum, which has the consistency of mortar when mixed with water, becomes porous when the water contained in it evaporates after application, and this situation causes the density of the gypsum to decrease and it becomes a lightweight material. Light materials ensure that the load on the building is less. In this case, the load transferred to the ground is less [45] which is beneficial for structural integrity and foundation requirement.

3.2.4 Fire resistance

Gypsum is a fire-safe material for protecting various structures like steel and wood. This is largely due to its water content, which makes up about 17% of its weight. When heated, this water turns to vapor, slowing down the overall heat increase. If a fire happens near gypsum, it starts a slow process called calcination, which begins on the surface and moves inward. This process slows as the outer calcined layer thickens, meaning nearby materials only heat up to a maximum of 150°C. Furthermore, the lightweight nature of gypsum reduces heat transfer [41].

3.2.5 Acoustic properties

Sound absorption and acoustic insulation are two important acoustic properties in building sectors. Acoustic insulation refers to material’s reduce sound transfer ability. Sound absorption, on the other hand, is the energy loss of sound upon contact with a material surface. Gypsum products, due to their low bulk weight offer limited sound insulation. While regular gypsum plaster isn't absorbent, gypsum with specific additives exhibits significant sound absorption. Gypsum plasterboard, a widely used gypsum product, positively impacts noise reduction by providing special acoustic grade that offers greater sound attenuation. The design of gypsum plasterboard allows a physical sound barrier, includes a sound break, and minimizes reverberation due to an air cavity between the board's two sides. This makes it harder for impact sounds to pass through, thus enhancing both sound insulation and absorption [40], [41].

3.3 Study Factory

The selected research area is the facilities located in the Southeastern Anatolia region of Türkiye, that produces powdered gypsum and gypsum plasterboard. The company operates two factories, producing gypsum plasterboard and powder gypsum. The gypsum factory not only produces base plaster for the gypsum plasterboard plant but also offers a range of products for various construction purposes. These include perlite gypsum plaster, satin plaster, machine gypsum plaster, plasterboard plaster, and grouting plaster.

In these facilities the plasterboard production process can be divided into three stages: raw material extraction, crushing, and grinding for the first stage; calcined powdered gypsum production for the second stage; and gypsum plasterboard production for the third stage.

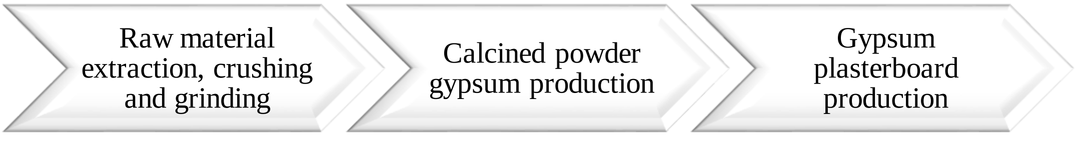

Figure 3.3 Plasterboard production process

Raw gypsum is extracted from mining quarries owned by the same company (Figure 3.4). The mining site covers a surface area of 1194 hectares and has an estimated 1373 million tons of reserves. On average, 17,000 tons of gypsum rock are extracted monthly. The gypsum mining site is located 25 kilometers from the powder gypsum factory. The gypsum rock, which is blasted and initially crushed at the mining site, is transported to the powder gypsum factory by trucks.

Figure 3.4 Gypsum mining quarries

The production facility of power gypsum covers an area of 39500 m^2 and has an annual production capacity of 300,000 ton. The company operates continuously, with three shifts per day, for 300 days each year.

The plasterboard production facility is located in the same area as the powder plaster production facility and covers an area of 20,000 m^2. The facility operates continuously, with three shift per day for 300 days and has an annual production capacity of 8,800,000 m^2. The plasterboard factory produces four types of plasterboard based on market demand: standard gypsum plasterboard, water-resistant gypsum plasterboard, fire-resistant gypsum plasterboard, and fire- and water-resistant plasterboard.

3.4 Gypsum and Plasterboard Production Processes

3.4.1 Raw material extraction

The production of plasterboard begins with the extraction of raw materials, which involves a blasting process in the mines. Blasting is conducted using precisely calculated quantities of explosives to crush the gypsum rock into manageable pieces.

Figure 3.5 Crushing unit

Following the blasting processes, the raw gypsum is transported to the crushing unit (Figure 3.5). Once the raw gypsum arrives at the crushing unit, it undergoes a series of crushing stages to reduce its size for further processing. The first step in the crushing process involves a jaw crusher. This machine is designed to handle large chunks of gypsum rock, breaking them down into smaller pieces typically ranging from 10 to 50 mm. The jaw crusher operates with a compressive force, which efficiently reduces the size of the raw material. After the initial size reduction, the material is transferred to a hammer crusher. The hammer crusher further crushes the gypsum pieces into finer particles, ensuring a more uniform size distribution. Following the crushing process, the gypsum particles are passed through a sieving system. The sieve sorts the crushed gypsum into different size fractions. The raw gypsum that meets the required size specifications (0-10 mm) is separated and conveyed to storage silos. The following diagram illustrates raw material extraction process in the production of plasterboard:

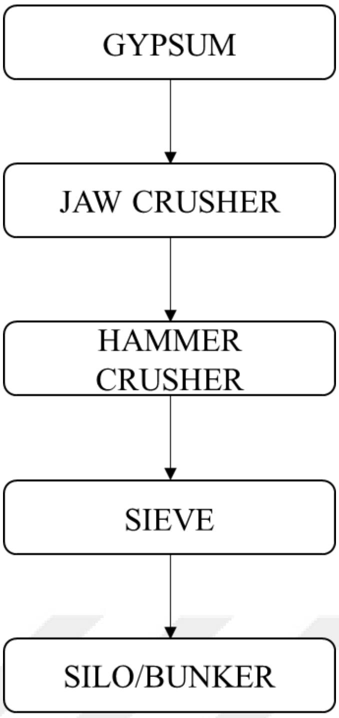

Figure 3.6 Raw material extraction process

Size reduction through crushing is an important step in the production of plasterboard. It not only facilitates the handling and processing of the material but also ensures that the gypsum can be effectively calcined in later stages. Properly sized gypsum particles improve the efficiency of the calcination process, leading to better quality and consistency in the final plasterboard product.

3.4.2 Calcined powder gypsum production

The raw gypsum is initially crushed to the desired dimensions at the mining sites before being transferred to the powder gypsum production factory. This preliminary crushing ensures that the gypsum is in a suitable form for the subsequent stages of processing. Once at the factory, the gypsum is moved to the rotary kilns for the calcination process.

The primary objective of the calcination process is to driving off three quarters of water from the gypsum stone, which has two moles of water in its natural form, and convert it into hemihydrate form. This transformation is crucial as hemihydrate gypsum, when mixed with water, forms a mortar that can be easily applied and will dry and harden to form a solid structure. Calcination occurs in two rotary kilns (Figure 3.7), one with a capacity of 20 tons per hour and the other with a capacity of 30 tons per hour. The gypsum is heated to temperatures of 130-150 °C, which facilitates the removal of water and the conversion to hemihydrate form.

Figure 3.7 Rotary kilns

Upon exiting the kilns, the calcined gypsum is conveyed to the base gypsum silo. From here, the gypsum intended for the production of plasterboard is transferred to the base gypsum silo within the plasterboard production plant via a blower-assisted conveying system. The remaining gypsum is then conveyed to the grinder, where it is milled to the desired sizes for the production of other gypsum products.

In the gypsum production facility, the gypsum that has been milled in the grinder is transported to the separator in the subsequent stage of the process, where it is classified into fine and coarse particle sizes. The separator's role is to ensure a precise separation, resulting in distinct fine and coarse gypsum fractions. These fractions are then directed towards different processing lines. The fine gypsum is used for products that require a smoother finish and finer texture, while the coarse gypsum is used for applications that demand greater structural integrity.

Figure 3.8 Separator (left) and grinder (right)

Following the separation, the process involves adding specific chemical additives to both the fine and coarse gypsum fractions to enhance their properties. These additives can include retarders, accelerators, and other performance-enhancing chemicals. The treated gypsum is then packaged for distribution. The thesis primarily concerns the production and processing stages preceding the production of gypsum plasterboard, excluding the final steps of additive incorporation and packaging in powdered gypsum plants for other gypsum products. The following diagram illustrates the sequence of operations involved in the production of gypsum products, starting from the calcination to the final packaging stages:

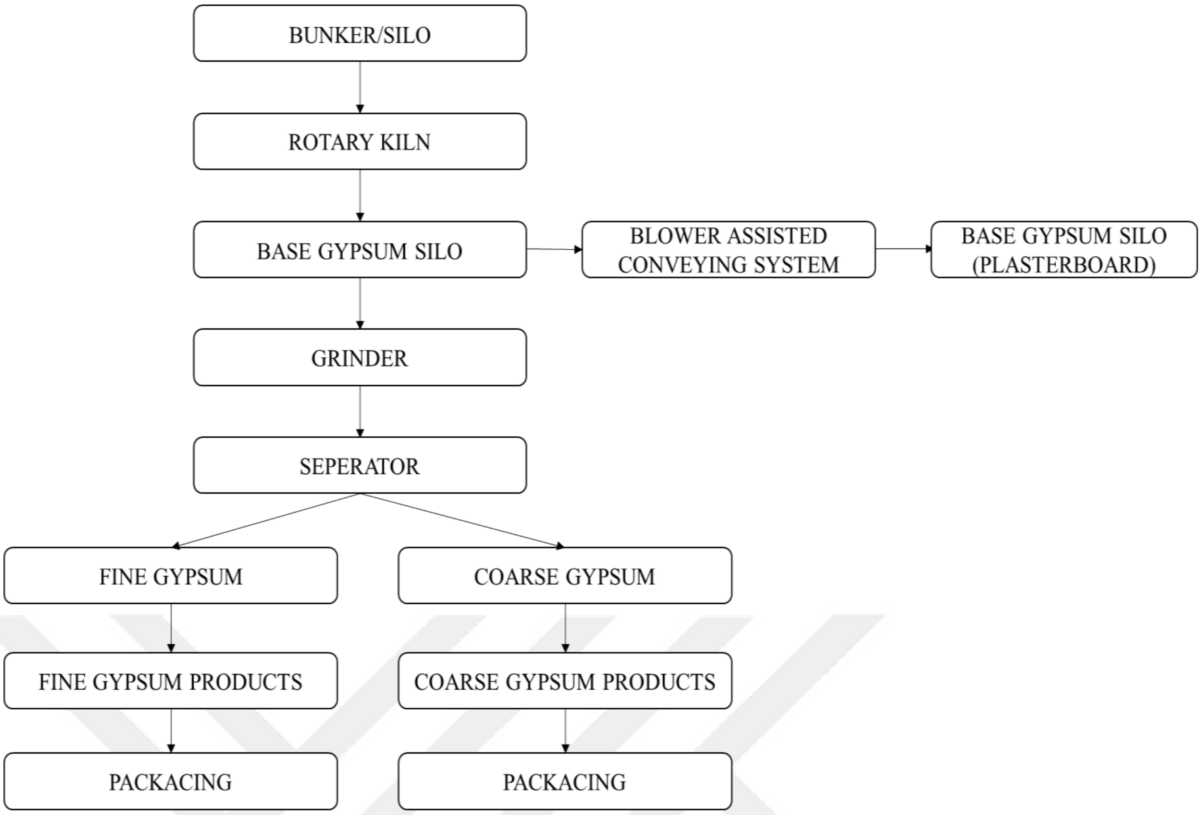

Figure 3.9 Calcined powder gypsum production process

3.4.3 Plasterboard Production

After three-quarters of the crystal water has evaporated, the base gypsum is transferred to the plasterboard silos using a blower-assisted conveying system. This prepared base material is then ready for the plasterboard production process. The process begins with the input of the bottom paper, which acts as a foundational layer for the board. Subsequently, a carefully formulated blend of gypsum, water, foam agent, and various chemical additives, collectively known as 'stucco', is poured onto this lower paper layer. To ensure the mixture is free of excessive air bubbles, air spraying and vibration techniques are employed, creating a uniform and stable base. The Figure 3.10 shows the mixer and the stucco being poured onto the bottom paper.

Following the preparation of the stucco layer, the bottom sheet is meticulously folded, and adhesive is applied to the areas where the top sheet will be placed. The top layer is then positioned over the gypsum mixture, which is compressed between the two sheets to achieve the desired fineness and thickness of the product. This composite is then conveyed through an 80-meter-long freezing conveyor, where it undergoes its initial setting phase. During this stage, the gypsum begins to harden, creating a solid core between the paper layers. Once the initial freezing is complete, the product is cut to the specified dimensions in the shearing stage, ensuring uniformity across all produced boards

Figure 3.10 Mixer and stucco

Following the preparation of the stucco layer, the bottom sheet is meticulously folded, and adhesive is applied to the areas where the top sheet will be placed. The top layer is then positioned over the gypsum mixture, which is compressed between the two sheets to achieve the desired fineness and thickness of the product. This composite is then conveyed through an 80-meter-long freezing conveyor, is shown in Figure 3.11-(a), where it undergoes its initial setting phase. During this stage, the gypsum begins to harden, creating a solid core between the paper layers. Once the initial freezing is complete, the product is cut to the specified dimensions in the shearing stage, ensuring uniformity across all produced boards

After the cutting process, the boards are carefully turned upside down to protect the application surface during the subsequent drying phase. The boards are then placed in a sophisticated dryer system, which consists of eight floors, each measuring 66 meters in length, and capable of holding two gypsum plasterboards per floor. The dryer is divided into two sections with opposing airflows to optimize the drying process. The first section maintains an average temperature of 115 °C, while the second section operates at around 130 °C. This controlled drying environment ensures that the boards achieve the desired moisture content and structural integrity.

Figure 3.11 (a) Freezing conveyor and (b) gypsum plasterboard plant

Upon completion of the drying process, one of the boards is flipped again using a specialized flipper mechanism, while the other remains in its original orientation. This flipping ensures that the product is shielded from external factors, as the two inner surfaces are packaged together. To finalize the production process, any burnt portions of the product are shaved away, resulting in smooth and clean edges. The boards are then packaged and prepared for storage, ready to be distributed for use in various construction applications.

In the Figure 3.11-(b), the gypsum plasterboard factory is shown with the paper input on the left side and the kiln output on the right side.

The diagram below illustrates the processes involved in gypsum plasterboard production within the plasterboard manufacturing facility.

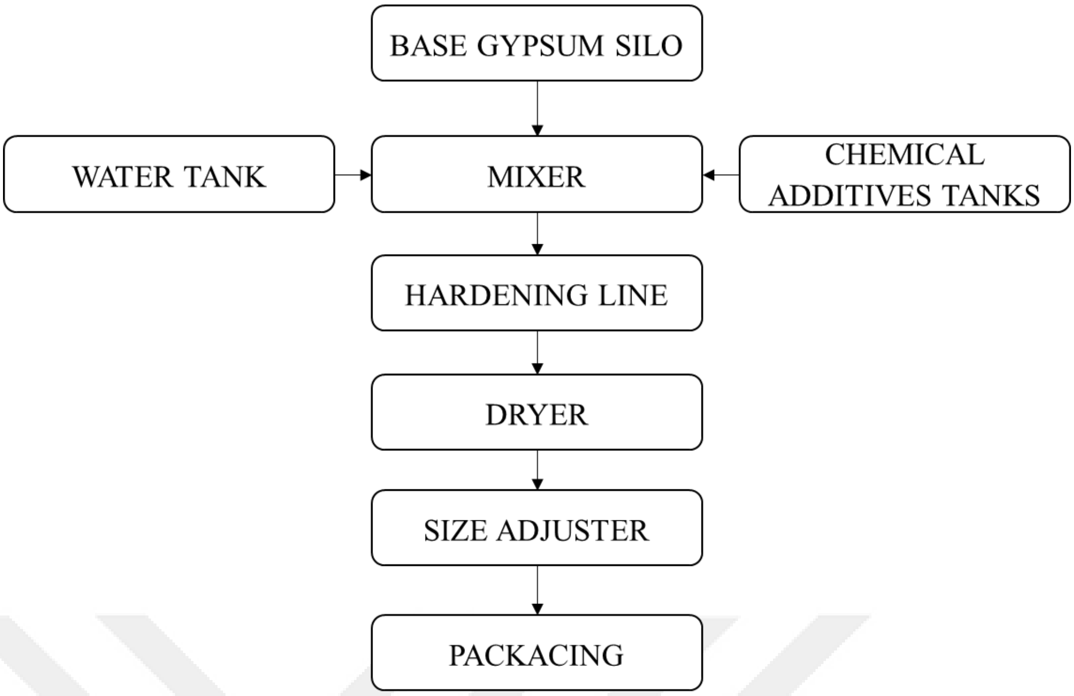

Figure 3.12 Plasterboard production process

3.5 Method

3.5.1 Water footprint (WF)

The WF was first introduced by Hoekstra at UNESCO-IHE in 2002. Following these initial studies, The Water Footprint Network has published The Water Footprint Assessment Manual [3], a guide to conducting initial water footprint studies and setting global standards for water footprinting.

The water footprint is a measure of water use that takes into account both direct and indirect use of water by a consumer or producer [46]. It consists of three components: blue, green, and grey water footprints. The blue WF is the loss of water from surface water and groundwater. The green water footprint is the use water from precipitation. The grey water footprint is a measure of the volume of freshwater required to assimilate the pollutants. The total water footprint is calculated as the sum of these three components (3.1) [3].

$$WF_{Total} = WF_{Blue} + WF_{Green} + WF_{Grey} \qquad (3.1)$$

The WF studies can be conducted for a process step, a product, consumers, a specific geographical region, a country, a catchment area or river basin, a municipality, or an enterprise. The present thesis concerns the water footprint of gypsum plasterboard products. The WF of a product, whether intermediate or final, is the sum of the water footprints of the various process steps involved in its production [3].

The blue, green and grey components of the WF of a product can be estimated by considering the water consumption and pollution in all stages of the production chain. The WF of an industrial product can be expressed in terms of either m^3 per US$ or water volume per piece [3]. In the case of the gypsum plasterboard product, the unit of liter water volume divided by the square meter product unit is employed (l/m^2), since production and sales are conducted in a square meter area.

The initial and most crucial step in the estimation of a product's WF is the comprehension of the product's production process. As industrial processes typically yield more than one final product, the assumption, simplification and schematic representation of the production system are also crucial steps [3].

Calculating the WF of a product's production process involves both direct water usage and indirect water usage which is mostly associated to the energy consumption. It is essential to account for the indirect WF when determining a product's overall WF. In gypsum plasterboard production, natural gas, diesel oil, and electricity are used. To calculate the WF of electricity, the sources of electricity produced in Türkiye were examined, and the indirect water footprint was calculated based on the proportions of electricity consumption (Table 3.1).

There are two ways for estimating the water footprint of a product: the chain-summation approach and the stepwise accumulative approach. In gypsum plasterboard production, there is actually a single product output so the chain-summation approach, which is the first method, is used in this thesis. In order to conduct a water footprint analysis, the system boundaries were defined as cradle-to-gate, with one square meter of plasterboard selected as the functional unit.

3.5.1.1 The chain-summation approach

This method can be applied only for the process which produces just one product. In this method, the water used or consumed at all stages of production can be attributed to a single product, as only one product exits the process. In production systems that produce more than one type of product, this method is not applicable, as the water consumed must be distributed to the products and double counting is to be avoided.

According to this method, the water footprint of product p (volume or mass) is calculated by the sum of the relevant process water footprints divided by the quantity of product p [3].

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \tag{3.2}$$

where;

WF_{proc} [s] is the process water footprint of step s (volume/time), and P[p] is the production quantity of product p (mass/time) [3].

3.5.2 Carbon Footprint (CF)

The concept of the CF is derived from the ecological footprint proposed by Wackernagel and Rees in 1996 [47]. According to this definition, the ecological footprint represents the area of sea and land required to sustain human life, while the CF denotes the area required to assimilate greenhouse gas emissions caused by humanity [48]. Despite the absence of a specific and comprehensive definition, the growing interest in carbon footprint studies underscores the need for a better understanding of the environmental impact of human activities.

According to Pandey et al. the CF refers to the quantity of greenhouse gases, expressed in CO_{2eq}, emitted into the atmosphere by an individual, organization, process, product or event within a specified limit. This definition underscores the wide-ranging sources of greenhouse gas emissions and highlights the importance of measuring and managing these emissions to mitigate climate change [48].

According to Wiedmann and Minx, CF is the overall quantity of carbon dioxide emissions related to an activity or gathered throughout the lifespan of a product, either directly or indirectly [49]. This approach includes emissions from all stages of a product’s life cycle, from raw material extraction through manufacturing, transportation, use, and disposal.

According to the Global Footprint Network, a CF can be understood as the amount of biocapacity necessary to absorb the carbon dioxide emissions produced by burning fossil fuels, a process largely facilitated by photosynthesis [49], [50]. Over time, the concept of the carbon footprint has been developed, with methods for its calculation determined and standards prepared. These methodologies aim to provide accurate and consistent measures of carbon emissions, facilitating comparisons and helping organizations and individuals to identify and reduce their CFs.

A variety of methodologies and standards have been developed for the calculation of greenhouse gas (GHG) emissions and CFs. One of these is the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines for national greenhouse gas inventories. These guidelines represent an updated version of the 1996 guidelines and provide a comprehensive framework for measuring and reporting GHG emissions.

The IPCC guidelines provide three different approaches to calculate direct or indirect CF, known as tier-1, tier-2 and tier-3. Tier 1 is a basic approach that uses national energy statistics to estimate emissions based on fuel consumption and average emission factors. Tier 2 improves accuracy by using country-specific emission factors and more detailed data on fuel types and combustion technologies. Tier 3 is the most complex and accurate method, employing detailed emission models or measurements at the individual plant level. Each tier approach is selected based on the quality of available data and resources, aiming to enhance the accuracy of emission estimates. Although the IPCC guidelines are primarily designed for use by countries to develop national GHG inventories, they can also be adapted for use at regional and city levels. [13].

The GHG Protocol methodology is another technique for the calculation of CFs. This approach, developed by the World Resource Institute and the World Business Council on Sustainable Development, provides a comprehensive framework for GHG accounting. It encompasses the measurement of seven key greenhouse gases, including CO_2, CH_4, and N_2O among others [51]. The methodology is divided into clear, actionable steps starting from defining organizational and operational boundaries to estimating the CF and finally reporting the results. The GHG Protocol also provides a suite of tools for the specific calculation needs of various sectors and projects, making it a versatile approach for a wide range of organizations. Its emphasis on not just the end results, but also on identifying effective reduction opportunities, makes it a strategic tool for organizations seeking to mitigate their environmental impact [52].

ISO 14064 is another recognized method for calculating CFs. This international standard consists of three parts. With a focus on boundaries, emissions quantification, and mitigation, it offers a comprehensive framework for developing greenhouse gas (GHG) inventories at the organizational level. It emphasizes the need for precise activity data collection and usage of specific emission factors. This standard has been an essential tool for organizations, aiding in the reliability of GHG quantification, facilitating GHG credits trade, and supporting the development of emission reduction strategies [52]. As the need for a common language to address GHG reduction grows, standards like ISO 14064 become increasingly important reference points in global efforts to mitigate GHG emissions.

The Life Cycle Assessment (LCA) method, another method for calculating the carbon footprint of a product or service, is a comprehensive approach. It covers every stage of a product's life, from raw material sourcing and production through distribution, utilization and final disposal. LCA provides a complete overview of the resources used, pollutants produced and greenhouse gases emitted at each stage. The ISO 14040-14044 and ISO 14025 standards represent a standardized framework for conducting LCA studies [48].

In order to calculate the CF of a product, the ISO 14067 standard is another method used for CF calculation. In accordance with this standard, product CF calculations are conducted with the life cycle assessment method, so it refers to ISO 14040, ISO 14044, ISO14026, ISO 14027 and ISO 14067 standards. This standard defines greenhouse gases as components of the atmosphere, both naturally occurring and anthropogenic, that possess the capacity to absorb and re-emit specific wavelengths of infrared radiation originally emitted by the Earth, its atmosphere and clouds. In order to compare the emission potency of various greenhouse gases, a unit called the "carbon dioxide equivalent" is utilized, which sets carbon dioxide as the baseline.

In this thesis, for the carbon footprint analysis the system boundaries were defined as cradle-to-gate, with one square meter of plasterboard selected as the functional unit. Data were directly obtained from the manufacturer, and carbon footprint calculations were performed using the IPCC Tier-1 approach, emission factors were sourced from the IPCC 2006 guidelines[13].

The emissions were calculated according to four categories: emissions from transport, emissions from natural gas consumption, emissions from electricity consumption, and emissions from water consumption. The following equation is used for the emissions to be calculated under these headings.

$$\text{Emissions} = \text{Consumption} \times \text{Emission Factor} \qquad (3.6)$$

In this thesis, carbon footprint calculations were made as annual and monthly analyses for the years 2021, 2022 and 2023.

3.5.3 Energy Footprint (EF)

The growing necessity for energy, driven by technological advances, individual energy consumption, and ecological concerns, has prompted researchers to assess the viability and efficiency of various energy conversion systems. This increased need has led to concerns regarding sustainability and the management of resources. Consequently, energy management and EF studies have become increasingly important. Although the concept of an EF is a commonly used term in the literature, there is no consensus regarding the definition and methods of this concept. Different definitions have been made for the term EF.

The Global Footprint Network defines EF as the sum of all land used to provide non-food and non-fodder energy [50]. The Living Planet Report prepared by World Wildlife Fund introduces the concept of the EF as a crucial element in the comprehension of the environmental impact of energy consumption. It accounts for four energy types – fossil fuels, biomass, nuclear, and hydro, representing the area needed to support a country’s energy use [53]. In order to ascertain the EF, another approach can be the calculation of energy consumption within parameters set by the Life Cycle Analysis methodology. The EF is an indicator that takes into account both the direct and indirect energy resources that are consumed during the production of goods and services. It attributes these energy resources to the ultimate consumer [54].

In his study, Muratoğlu [5] redefined the concept and methodology of the EF and aimed to distinguish it from the Ecological Footprint. The author highlights the shortcomings of existing methodologies and propose a novel approach inspired by the WF methodology. This approach considers all types of energy resources and the total energy consumption in the production or supply chain of goods and services. The EF is aimed at improving environmental sustainability and facilitating effective energy management. It does not account for energy consumed in the formation of natural materials, focusing only on energy used in human activities. The study also introduces the concept of different "colors" for different types of energy based on their production risks and environmental impact. In this study, the methodology that is reported by Muratoglu [5] was used to determine the energy footprint.

The calculation of the EF must consider the source and type of energy due to their varying environmental impacts and economic values. The study acknowledges this by associating a distinct color with each energy type. This color-coding system, which is based on the production risks linked to each energy type, allows for a more transparent representation of the energy consumed. Thus, even if two processes have the same EF, the environmental and economic implications can differ significantly depending on the energy type [5]. The Figure below shows the colors assigned to energies and energy sources.

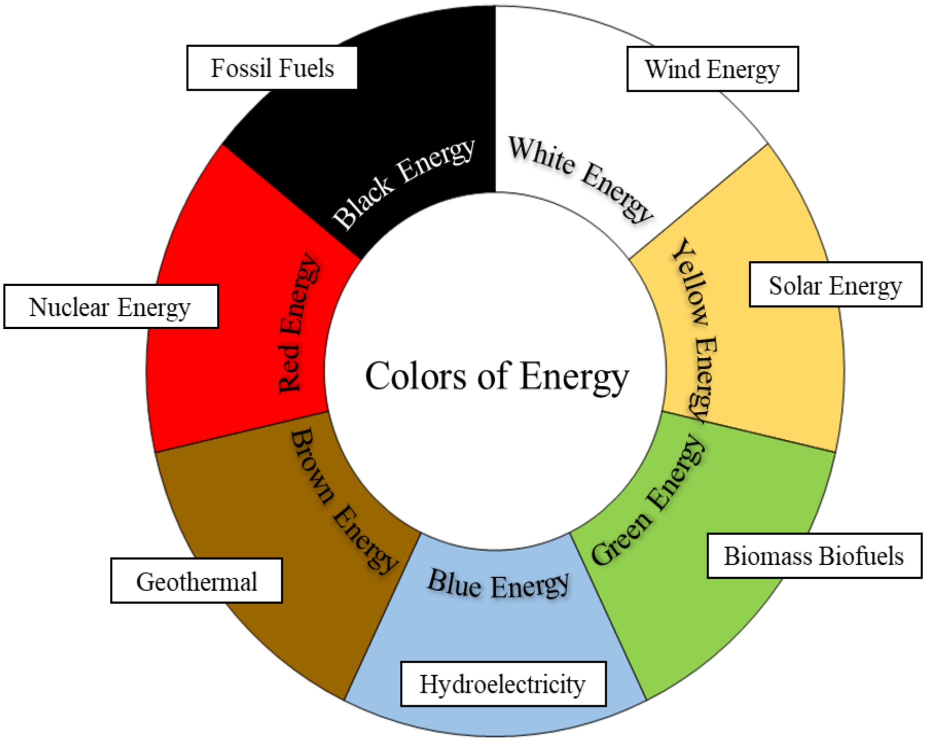

Figure 3.13 The colors of energy based on Muratoglu [5]

The EF is measured using a unit that primarily represents energy. Various energy units like kWh, J, Cal, and Btu can be used. The EF can be expressed per unit area, time, mass or production quantity for comparability across sectors. It allows comparison of energy intensity among different products and processes, guiding individuals, organizations, and countries to reduce energy consumption [5].

The EF is calculated using the following formula (3.7):

$$EF = \frac{E_c}{P} \qquad (3.7)$$

where; EF is Energy footprint (MJ/m^2), E_c is Consumed Energy (MJ), P is the production amount (m^2)

3.6 Data

This study collected monthly data for the years 2021, 2022, and 2023 from each production process to conduct water, carbon, and energy footprint analyses in order to determine the environmental impacts of gypsum plasterboard production.

The data used for WF, CF and EF calculations include the following:

- Total gypsum plasterboard production quantities (m^2): regularly reported by the facility. In the footprint calculations, 1 m^2 of gypsum plasterboard is used as the functional unit. Therefore, the monthly calculated data are divided by the total production quantities to determine the footprint per unit of production. The production data are used for this purpose for WF, CF, and EF calculations.
- Direct Water consumption (l): There is no direct water use in the raw gypsum extraction and transportation process. Water consumption data for personnel and processes at the PGP and PP are measured by water meters installed at the facilities, and data are obtained from these meters. This data used for WF analysis.
- Natural gas consumption (m^3): Natural gas is used as a fuel in the dryers located at the PGP and PP. Natural gas consumption is regularly measured using natural gas meters, and the consumption quantities are regularly reported by the facilities. The data are obtained directly from these reports. Natural gas consumption contributes to the indirect WF due to its production and distribution processes, and this data is used in the calculation of the indirect WF. Additionally, natural gas usage in the facilities directly contributes to

carbon emissions, and this data is utilized in the CF calculation. As a significant energy input, it is also included in the EF calculation.

- Diesel oil Consumption (l): Diesel oil is primarily used as fuel for transporting raw materials to the facilities, forklifts and other vehicles within the facility, and transporting personnel. The amount of diesel used for raw material transportation and facility vehicles is continuously monitored, with data obtained from facility reports. For personnel transportation, since it is handled by an external company and not regularly reported, data were obtained directly from the transportation company and estimations were used to fill in any missing data. For gypsum plasterboard production, both PP and PGP operate 24 hours a day in three shifts. Each shift has totally 14 employees, and a shuttle bus is used for each shift, meaning three shuttles use fuel daily to transport employees to the facility. The estimates were made with these considerations in mind. Diesel fuel consumption contributes to the indirect WF due to its production and distribution and causes direct carbon emissions, making it a factor in the CF calculation. Additionally, as a significant energy input, it is included in the EF calculation.
- Electricity consumption (kWh): In gypsum plasterboard production, electricity is used to operate crushers for raw materials, and to power dryers, grinders, elevators, and all machinery at the PGP and PP. All electricity consumption is regularly measured by electricity meters and reported by the facilities. The data on electricity usage were obtained directly from these reports. Electricity consumption contributes to indirect carbon emissions, and this data was used in the CF calculations. Although electricity itself is not an energy source, it is generated using various energy sources and water is consumed in its production. Therefore, this data is also used in the calculations of the indirect WF. Additionally, the energy sources used for electricity generation constitute a significant portion of energy consumption, and this data was used in the energy footprint (EF) calculation. However, since the direct source of the electricity used in the facilities is unknown, the distribution of the total electricity produced in Türkiye was considered in this study, and the footprints were allocated accordingly. The table below shows the distribution of electricity sources in Türkiye for the years 2021-2023, with data obtained from TEİAŞ [55].

Table 3.1 Distribution of energy sources for electricity production in Türkiye [55]

Year	Coal	Lignite	Natural Gas	Hydro-Energy	Geothermal+Wind+solar	Other
2021	18.04%	12.84%	33.22%	16.71%	16.78%	2.41%
2022	20.88%	13.75%	22.86%	20.34%	19.17%	3.00%
2023	23.71%	12.54%	21.38%	19.56%	19.54%	3.05%
Average	20.88%	13.04%	25.82%	18.87%	18.50%	2.82%

Literature-based WF values of energy sources were used to calculate the indirect water footprint. The WF values for natural gas, coal, and lignite were obtained from Mekonnen at al. study [56], while the WF of diesel oil was referenced from Bosman's study [57]. The water footprint of hydroelectric energy was calculated based on a study conducted on the Atatürk Dam in Türkiye [58], (Table 3.2).

Table 3.2 The Water footprint of energy sources (Data is based on [56], [57], [58])

Energy source	**$WF_{h,f}$ [L/GJ]**
Coal	6.6–228(15)
Lignite	12–48(15)
Natural gas	0.6–18(2.2)
Hydro-Energy	57100
Diesel	28 – 376 (80)

CHAPTER 4

RESULTS

This chapter presents the results of the water, carbon, and energy footprint analyses to determine the environmental impacts of the gypsum plasterboard product. The Figure 4.1 illustrates all Process of gypsum plasterboard production and the associated footprint at each Process. Accordingly, the entire process is divided into three sections: raw material extraction and transportation, powder gypsum production, and gypsum plasterboard production. In the processes, the WF is represented by blue footprint symbols, the CF by green footprint symbols, and the EF by yellow footprint symbols.

The direct WF originates from personnel usage in the powder gypsum plant and is utilized in the slurry formation processes within the gypsum plasterboard plant. The indirect WF resulting from energy use is present at all stages and has been indicated accordingly. Direct carbon emissions are primarily due to natural gas consumption in the dryers. Since all facilities operate with electricity, there are carbon emissions associated with electricity consumption at all facilities, as illustrated in the graph. The energy footprint resulting from the use of electricity, natural gas, and diesel fuel is also depicted in Figure 4.1.

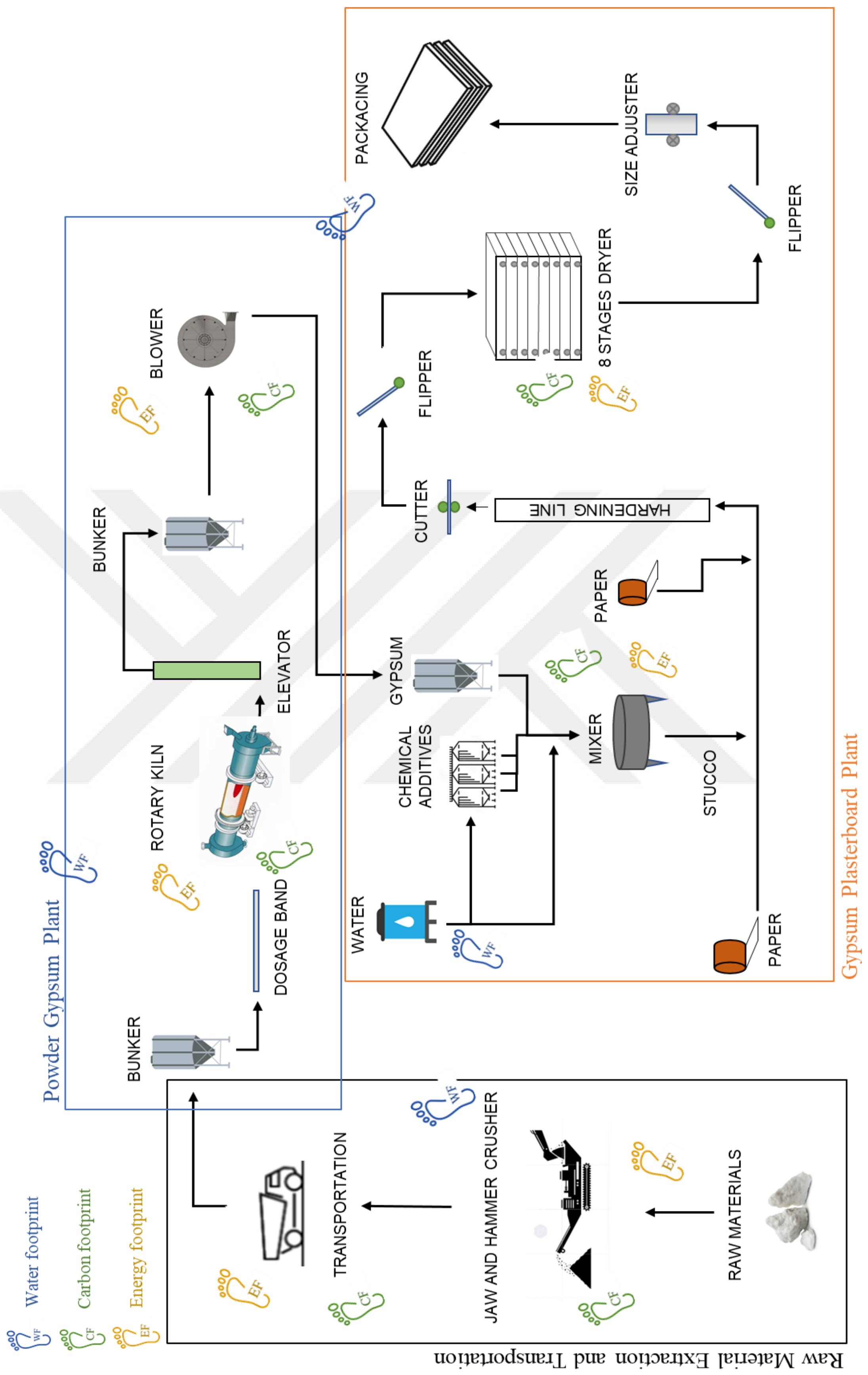

Figure 4.1 Gypsum plasterboard production process and associated footprints

4.1 Water Footprint

4.1.1 Direct Water Footprint

In the raw material extraction, crushing, and grinding processes, no water is utilized, indicating that these initial stages do not contribute to the direct water footprint. Additionally, in the calcined powder gypsum process, water consumption is minimal and is only attributed to personnel usage, making this stage relatively insignificant in terms of overall water consumption.

The most significant and primary direct water consumption occurs during the gypsum plasterboard production phase. In this critical phase, water is predominantly used in the transformation of powdered gypsum into a slurry form, which is essential for the manufacturing of gypsum plasterboards. The amount of water used in the preparation of the slurry can vary depending on the purity of the base gypsum, weather conditions, and the specific formulations that include various auxiliary chemicals, which can significantly influence the consistency and quality of the final product.

Table 4.1 presents the WF values (l/m^2) for the gypsum plasterboard product, detailing the water footprints at both the powder gypsum plant (PGP) and the plasterboard plant (PP). The table provides comprehensive data for the years 2021, 2022, and 2023, illustrating the individual direct WFs for each year.

Table 4.1 Water footprint of plasterboard for years 2021, 2022, and 2023 (l/m^2)

Year	PGP	PP	Total
2021	0.390	5.773	6.163
2022	0.470	5.988	6.458
2023	0.291	5.589	5.880
Average	0.383	5.784	6.167

Calculating the WF on a monthly basis over a three-year period revealed that the average WF of gypsum plasterboard is 6.167 l/m^2.

To identify the seasonal water consumption patterns of gypsum plasterboard production, the average monthly water footprint values were calculated over a three-year period, as shown in the Figure 4.2.

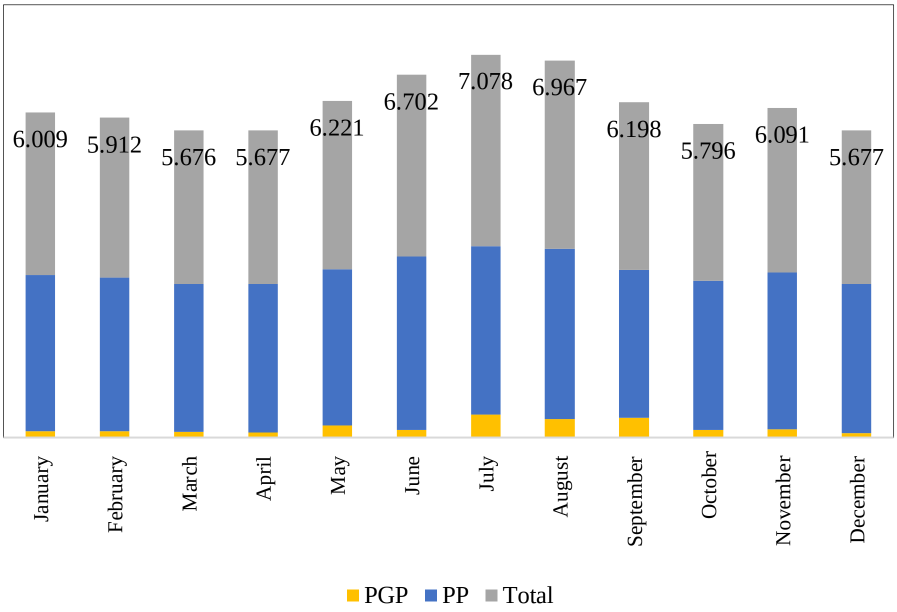

Figure 4.2 Average monthly WF of plasterboard

The Figure4.2 reveals fluctuations in water use across different months, with the highest water footprints recorded in July and August (7.078 l/m^2 and 6.967 l/m^2, respectively) and the lowest in March and April (5.676 l/m^2 and 5.677 l/m^2, respectively). The majority of water consumption is consistently attributed to the PP. Notably, water usage increases during the summer months primarily due to increased personal water consumption by employees for personal activities. Furthermore, changes in water usage are also dependent on the purity of the raw material and the calcination rate, specifically the crystal water content or the loss on ignition, of the gypsum coming from the powder gypsum plant.

As shown in the Figure 4.3, the total direct WF of the gypsum plasterboard product is 6.167 l/m^2. It is observed that 93.78% of this footprint is attributed to the slurry formation process in the PP, while 6.22% is due to personal water usage in the PGP.

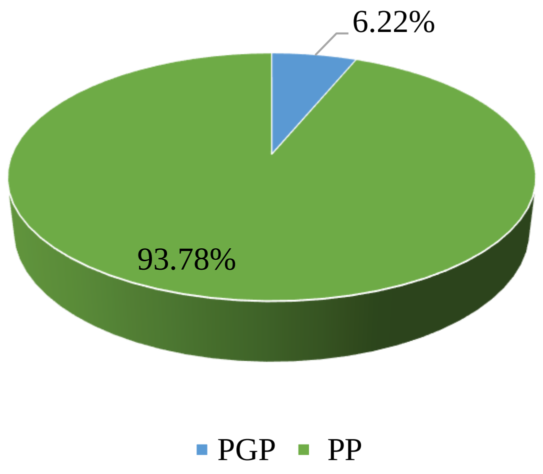

Figure 4.3 Distribution of WF in Gypsum plasterboard Production

Additionally, it is important to note that all the water used in the factories is sourced from municipal supplies, classifying it entirely as blue water.

4.1.2 Indirect Water Footprint

In gypsum Plasterboard production, indirect water usage is attributed to the natural gas used in the dryers at both the powder gypsum and board plants, the diesel oil used as fuel for raw materials, personnel, and forklifts within the facility, and the electricity that powers all machinery. Since the direct source of electricity supplied to facilities is unknown, the sources and proportions of gross electricity produced in Türkiye were investigated (Table 3.1). The water footprint was then calculated based on the proportions of the electricity production sources. The WF data for energy sources (Table 3.2) were multiplied by our energy consumption data to calculate the indirect water footprint. The indirect WF of gypsum plasterboard production was calculated to be 22.28 l/m^2.

The indirect WF plays a significant role in production processes, accounting for 78.33% of the total WF (figure 4.4). This highlights the substantial impact of energy consumption on water resources. Among energy sources, hydropower is the most significant contributor to the water footprint.

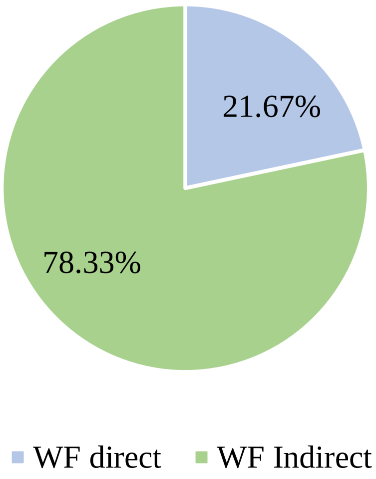

Figure 4.4 Direct and indirect WF for Plasterboard production

The average annual WF of gypsum plasterboard production, including both direct and indirect usage, was calculated to be 28.45 l/m^2. Figure 4.5 reveals that the largest impact, accounting for 83.96%, originates from the PP. The primary reasons for this are the direct water usage in slurry formation and the electricity consumption. Following this, the PGP accounts for 13% of the WF, while RME and RMT 2.48%.

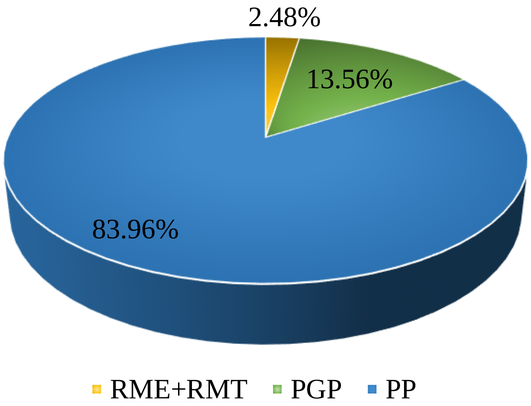

Figure 4.5 Distribution of Total WF by Proses

4.2 Carbon Footprint

The direct carbon emissions at the factory are primarily caused by the utilization of natural gas and diesel. Natural gas is used in the dryers for the purpose of heating, while diesel is used for operating forklifts and other vehicles and transportation activities. Indirect carbon emissions, on the other hand, result from the consumption of electricity and water. Electricity is used to operate machinery within the factory, and during the raw material extraction phase to power crushers.

4.2.1 Emissions from Natural Gas Consumption

The CF associated with natural gas usage was calculated using the IPCC Tier-1 approach. This methodology incorporates the emission factors, net calorific values of fuels, and carbon contents as specified in the IPCC 2006 guidelines. These parameters were used in the calculation process [13].

The following equations were used to calculate greenhouse gas emissions from natural gas:

$$\text{Emissions}_{\text{GHG}} = \text{Consumption} \times \text{Emission Factor} \quad (4.1)$$

where; Emissions $_{\text{GHG,}}$ = Emissions of given GHG by natural gas (kg GHG), Consumption = Amount of natural gas (TJ), Emission Factor $_{\text{Natural Gas}}$ = Default emission factor of a given GHG (kg gas/TJ). For CO_2, it includes the carbon oxidation factor, assumed to be 1.

Equation 4.1 indicates that the amount of fuel used for the calculations should be expressed in terms of energy rather than mass. The net calorific values (NCV) of the fuels must be utilized to convert the fuel consumption into energy units. According to the IPCC guidelines, the NCV of natural gas is 48.0 TJ/Gg, Emission Factor is 56.1 Ton CO_2/TJ and the density is 0.68 kg/m^3.

In gypsum plasterboard production, natural gas is consumed in two stages. Firstly, it is used in the powder gypsum production plant to evaporate the crystalline water from the raw gypsum, transforming it into a usable plaster. Secondly, it is employed in the gypsum plasterboard plant for drying the boards in the dryers.

The table below shows the monthly average natural gas consumption for the factories for the study period.

Table 4.2 Average natural gas consumptions in PGP and PP

Year	**Natural gas consumption in PGP (m^3/m^2)**	**Natural gas consumption in PP (m^3/ m^2)**
2021	0.129	0.393
2022	0.172	0.399
2023	0.167	0.396

The greenhouse gases resulting from natural gas consumption include CO_2, CH_4, and N_2O. Accurate quantification of the overall CF requires calculating the emissions of these gases using Equation 4.1. Subsequently, they are converted to CO_2 equivalents according to IPCC 2006 guidelines. According to these guidelines, the global warming potential (GWP) of CH_4 is 28, with a NCV conversion factor of 0.001 tons CO_2/TJ. Similarly, the GWP of N_2O is 265, with an NCV conversion factor of 0.0001 tons CO_2/TJ.

An example calculation of emissions from natural gas for January 2021 is presented below:

- Natural gas consumption: 354343 m^3
- Net calorific value: 48 TJ/Gg
- Emission factor for CO_2: 56.1 tons CO_2/TJ
- Emission factor for CH_4: 0.001 tons CO_2/TJ
- Emission factor for N_2O: 0.0001 tons CO_2/TJ
- Natural gas density: 0.68 kg/m^3
- GWP of CO_2 is 1
- GWP of CH_4 is 28
- GWP of N_2O is 265

For CO_2 Emission:

$$CO_2\ Emission = 354343\, m^3 \times \frac{56.1\, ton\ CO_2}{TJ} \times \frac{48\, TJ}{Gg} \times \frac{Gg}{1000000\, kg} \times \frac{0.68\, kg}{m^3}$$
$$= 648.83\, ton\ CO_2 / month$$

For CH_4 Emission:

$$CO_2\ Emission = 354343\,m^3 \times \frac{0.001\,ton\,CO_2}{TJ} \times \frac{48\,TJ}{Gg} \times \frac{Gg}{1000000\,kg} \times \frac{0.68\,kg}{m^3} \times 28$$

$$= 0.32\,ton\,CO_2\,/\,month$$

For N_2O Emission:

$$CO_2\ Emission = 354343\,m^3 \times \frac{0.0001\,ton\,CO_2}{TJ} \times \frac{48\,TJ}{Gg} \times \frac{Gg}{1000000\,kg} \times \frac{0.68\,kg}{m^3} \times 265$$

$$= 0.306\,ton\,CO_2\,/\,month$$

Total CO_2 Emissions = 648.83 + 0.32 + 0.306 = 649.456 ton CO_2 / month

Based on the monthly calculations for the years 2021, 2022, and 2023, the emissions from natural gas consumption per square meter of gypsum plasterboard production have been determined to be 1.014 kg CO_2/m^2. Specifically, for the powder gypsum production plant, the emission amount is calculated to be 0.286 kg CO_2/m^2, while for the gypsum plasterboard production facility, it is 0.727 kg CO_2/m^2.

It has been observed that 28% of the emissions from natural gas consumption originate from the powder gypsum plant, while 72% originate from the gypsum Plasterboard production plant.

The following graph illustrates the monthly average emissions from natural gas consumption per square meter of gypsum plasterboard production for the years 2021, 2022, and 2023, for two facilities.

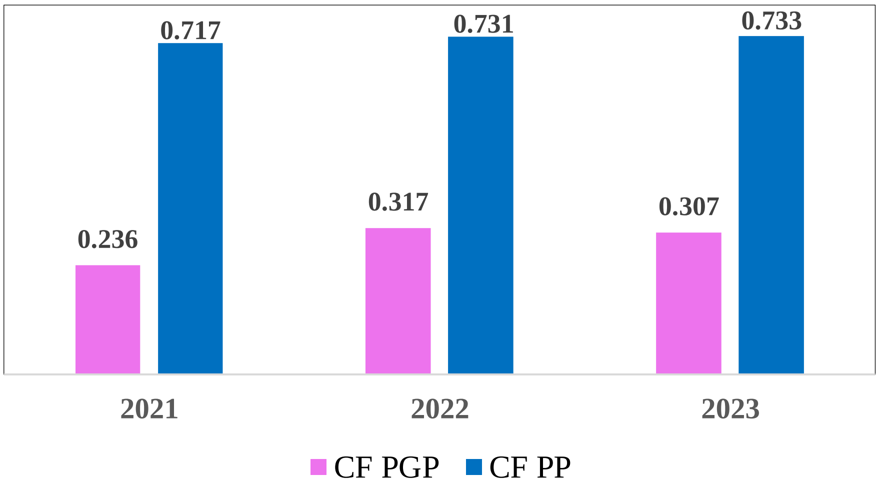

Figure 4.6 CF resulting from natural gas consumption

4.2.2 Emissions from Diesel Oil Consumption

In gypsum plasterboard production, one of the sources of carbon emissions is the use of diesel oil. This section calculates the CF resulting from diesel oil, which is commonly used as vehicle fuel in the facilities.

In the gypsum plasterboard production processes, the consumption of diesel oil for raw material transportation, personnel shuttles, and factory vehicles results in CO_2, CH_4, and N_2O emissions. The following equation has been used to calculate these emissions:

$$\text{Emissions} = \text{Consumption}_{\text{Diesel oil}} \times \text{Emission Factor}_{\text{Diesel oil}} \qquad (4.2)$$

Where; Emissions = GHG Emissions from Diesel oil (kg GHG), Consumption $_{\text{Diesel oil}}$ = Amount of Natural gas (TJ), Emission Factor $_{\text{Diesel oil}}$ = Default emission factor of a given GHG (l /TJ).

Similar to the calculation of carbon emissions from natural gas, the equation used here expresses the amount of fuel in energy units (TJ). To convert these energy units to fuel consumption, NCV must be used. According to IPCC guidelines, NCV of diesel oil is 43 TJ/Gg, Emission factor is 74.1 Ton/TJ and density is 0.835 kg/l.

Presented below is an example calculation of emissions from Diesel oil for January 2021:

- Consumption of diesel oil is = 4166 L (RMT) + 469 L (PGP) + 507 L (ET) =5142 L

- NCV = 43 TJ/Gg
- Emission factor = 74.1 Ton/TJ
- Emission factor for CH_4: 0.0039 Ton CO_2/TJ
- Emission factor for N_2O: 0.0039 Ton CO_2/TJ
- Density = 0.835 kg/L
- GWP of CO_2 is 1
- GWP of CH_4 is 28
- GWP of N_2O is 265

For CO_2 Emission:

$$CO_2\ Emission = 5142\ L \times \frac{74.1\, ton\, CO_2}{TJ} \times \frac{43\, TJ}{Gg} \times \frac{Gg}{1000000\, kg} \times \frac{0.835\, kg}{L}$$
$$= 13.68\, ton\, CO_2\ /\ month$$

For CH_4 Emission:

$$CO_2\ Emission = 5142\ L \times \frac{0.0039\, ton\, CO_2}{TJ} \times \frac{43\, TJ}{Gg} \times \frac{Gg}{1000000\, kg} \times \frac{0.835\, kg}{L} \times 28$$
$$= 0.0202\, ton\, CO_2\ /\ month$$

For N_2O Emission:

$$CO_2\ Emission = 5142\ L \times \frac{0.0039\, ton\, CO_2}{TJ} \times \frac{43\, TJ}{Gg} \times \frac{Gg}{1000000\, kg} \times \frac{0.835\, kg}{m^3} \times 265$$
$$= 0.1908\, ton\, CO_2\ /\ month$$

Total CO_2 Emissions = 13.68 + 0.0202 + 0.1908 = 13.891 ton CO_2 / month

The calculations have shown that the greenhouse gas emissions resulting from diesel oil consumption have been calculated monthly for the study period. On average, the emissions amount to 0.0229 kg CO_2 per square meter of gypsum plasterboard production.

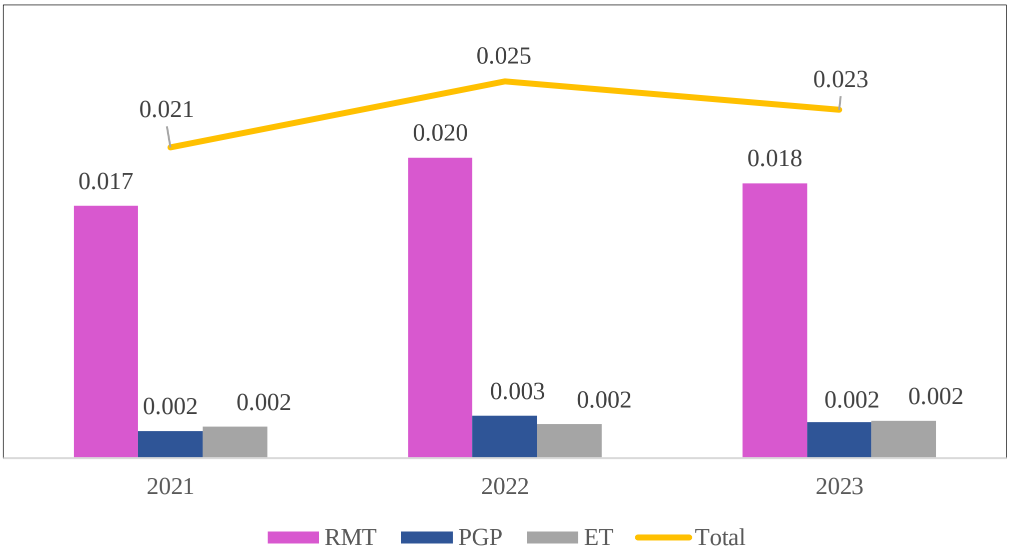

Figure 4.7 CF from diesel oil

The distribution of emissions from diesel fuel consumption by year and process is shown in Figure 4.5. The graph shows that the majority of emissions from diesel consumption are due to the transportation of raw materials.

4.2.3 Emissions from Electricity Consumption

Electricity consumption for gypsum plasterboard production is utilized at various stages of the manufacturing process. Specifically, electric energy is used to operate crushers during the raw material extraction process. Additionally, electricity is consumed to power various machines in both the powdered gypsum and plasterboard facilities. To calculate the CF resulting from electricity consumption, direct electricity consumption data has been collected from the company.

The carbon emissions resulting from electricity consumption are calculated using the following equation:

$$\text{Emissions}_{\text{Electricity}} = \text{Consumption}_{\text{Electricity}} \times \text{Emission Factor} \quad (4.3)$$

Where $\text{Emissions}_{\text{Electricity}}$ = Emissions from electricity consumption (kg CO_{2eq}), $\text{Consumption}_{\text{Electricity}}$ = Electricity consumption (kWh), Emission factor = Default emission factor (kg CO_2/kWh)

For the CF calculation, the emission factor is taken as 0.7279 based on the current National Grid Emission Factor for Türkiye, published by the Ministry of Energy and Natural Resources of the Republic of Türkiye.

An example of calculating emissions from electricity consumption for gypsum plasterboard production is shown below for January 2021.

Electricity Consumption = 337675 kWh

Emission factor = 0.7279 kg CO_2/kWh

$$CO_2\ Emission = \frac{337675\ kWh \times 0.7279\ kg\ CO_2\ /\ kWh}{\dfrac{1000\ kg}{ton}}$$

$$= 245.79\ ton\ CO_{2eq}$$

Dividing the amount of electricity consumed by the amount of gypsum plasterboard produced allows for the calculation of emissions from electricity consumption per square meter for the RME, the PGP, and the PP for the study period. The calculations for the three years indicate that the average total carbon emissions from electricity consumption for producing one square meter of gypsum plasterboard is 0.417 kg CO_2/m^2. The carbon emissions resulting from electricity consumption for each plant over these three years are illustrated in the graph below (Figure 4.6).

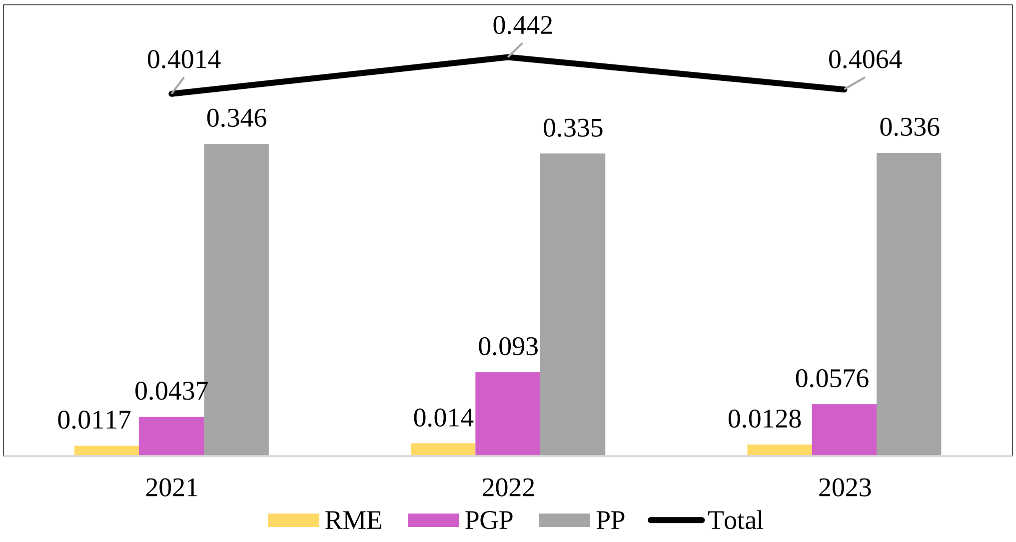

Figure 4.8 CF from electricity consumption

There is no significant difference in the amount of carbon emissions from electricity consumption over the three years. However, an increase in electricity consumption is noticeable in the powdered gypsum production facility in 2022, which is attributed to the incoming raw materials.

The Figure 4.7 illustrates the CF from electricity consumption by facility. According to the graph, the highest electricity consumption for gypsum plasterboard production occurs in the gypsum plasterboard production facility, while the lowest consumption occurs in the raw material extraction facility.

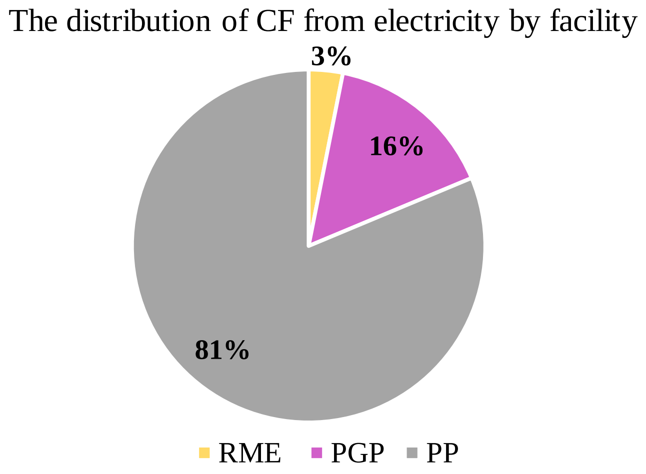

Figure 4.9 The distribution of CF from electricity by facility

4.2.4 Emissions from Water Consumption

In the gypsum plasterboard production process, water is primarily consumed in the gypsum plasterboard plant to make the slurry. Additionally, water consumption in the gypsum facility, including water used by personnel, is also considered. The CF from water consumption has been calculated using the equation provided below.

$$\text{Emissions}_{\text{water}} = \text{Consumption}_{\text{water}} \times \text{Emission Factor}$$

Where $\text{Emissions}_{\text{Water}}$ = Emissions from Water consumption (kg CO_{2eq}), $\text{Consumption}_{\text{water}}$ = Electricity consumption (L), Emission factor = Default emission factor (kg CO_2/L)

In the calculations, an emission factor of 0.0014 kg CO_{2eq}/L has been used [59], [60]. An example calculation for January 2021 is shown below.

Water Consumption = 3436 m^3

$$CO_2\ Emission = \frac{(3436\,m^3 \times 1000\,\frac{L}{m^3}) \times 0.0014\,kg\ CO_2\,/\,L}{\frac{1000\,kg}{ton}}$$

$$= 4.81\,ton\ CO_{2eq}$$

Dividing the monthly water consumption related emissions by the production amount data calculates the CF from water consumption per square meter of production for the study period. The calculations indicate that, on average, 0.0087 kg of carbon emissions are produced for each square meter of gypsum plasterboard.

The graph below shows the CF from water consumption by year. No significant changes in water consumption are observed across the years.

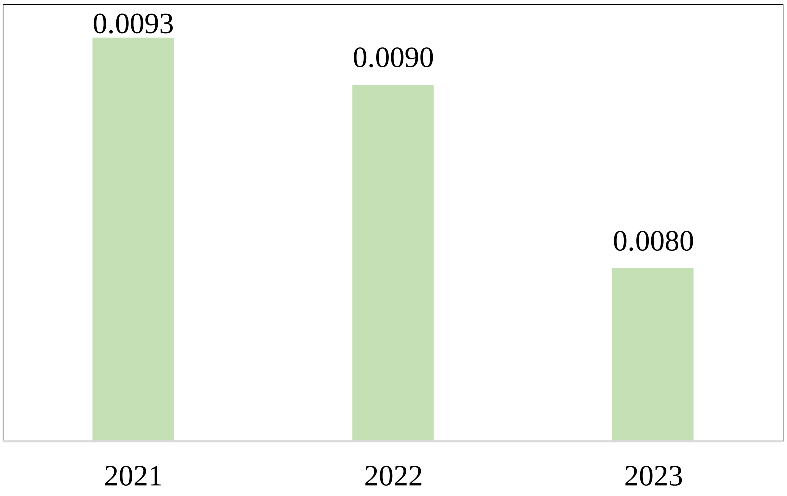

Figure 4.10 CF from electricity consumption

4.2.5 Total Carbon Footprint

In Section 4.2, the direct and indirect carbon emissions resulting from all processes involved in gypsum plasterboard production, from cradle to factory gate, were calculated on a monthly basis over a three-year period. Considering all emissions, it was determined that the CF of gypsum plasterboard is 1.463 kg CO_{2eq}/m^2.

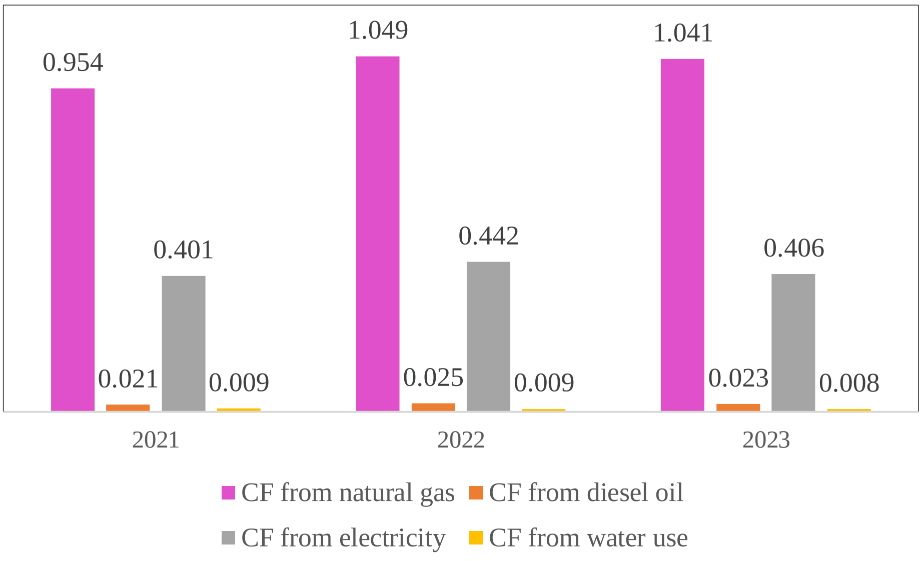

Figure 4.11 Distribution of CF by different sources

The Figure 4.11 illustrates the distribution of the CF of gypsum plasterboard production by source for the study period. According to the graph, natural gas consumption is the largest source of carbon emissions. This is followed by electricity consumption, which also has a significant CF. The CF from diesel fuel usage and water consumption is relatively low compared to the other sources.

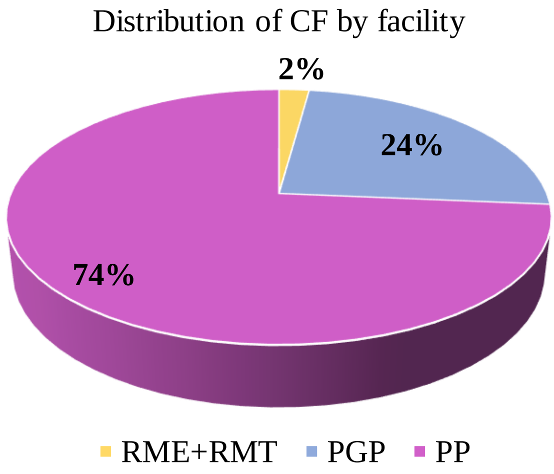

Figure 4.12 Distribution of CF by facility

Figure 4.12 illustrates the distribution of the CF by facility. Among all processes involved in gypsum plasterboard production, the highest emissions occur in the plasterboard plant accounting for 74% of the total. The lowest emissions, at 2%, are generated during raw material extraction and transportation.

4.3 Energy Footprint

4.3.1 Raw gypsum extraction and transportation

The primary energies used in the raw material extraction and transportation processes are electricity and diesel oil.

Table 4.3 EF (MJ/m^2) of raw material extraction and transportation

Year	RME Electricity						RMT Diesel oil	Total
	Coal	Lignite	Natural gas	Hydro-energy	Geothermal +wind +solar	Other		
2021	0.012	0.008	0.015	0.011	0.011	0.002	0.239	0.297
2022	0.014	0.009	0.018	0.013	0.013	0.002	0.285	0.354
2023	0.013	0.008	0.016	0.012	0.012	0.002	0.259	0.323

The Table 4.3 presents the EF (MJ/m^2) of the raw material extraction and transportation stages of gypsum plasterboard production for the study period. The EF for raw material extraction and transportation accounts for 1.375% of the total EF of gypsum plasterboard production.

4.3.2 Powder Gypsum Plant

The primary energy sources used in the powder gypsum plant are natural gas, electricity, and diesel oil. The Table 4.4 shows the EF (MJ/m^2) for the powder gypsum plant, which is the second stage of gypsum plasterboard production. The powder gypsum production stage accounts for 26.918 % of the total EF of gypsum plasterboard production.

Table 4.4 EF (MJ/m^2) of powder gypsum plant

Year	PGP Electricity						PGP Diesel oil	PGP Natural gas	Total
	Coal	Lignite	Natural gas	Hydro-energy	Geothermal +wind +solar	Other			
2021	0.045	0.028	0.056	0.041	0.040	0.006	0.026	4.935	5.177
2022	0.096	0.060	0.119	0.087	0.085	0.013	0.040	6.631	7.132

2023	0.059	0.037	0.074	0.054	0.053	0.008	0.035	6.418	6.738

4.3.3 Gypsum Plasterboard plant

The primary energy sources used in the final stage of gypsum plasterboard production, in the plasterboard plant, are electricity, natural gas, and diesel oil for employee transportation. Since the company's powder gypsum and gypsum plasterboard plants are located at the same site, the energy footprint from employee transportation is calculated in this section. The table below shows the EF (MJ/m^2) for this stage. The EF of the gypsum plasterboard plant accounts for 71.707% of the total energy footprint of gypsum plasterboard production.

Table 4.5 EF (MJ/m^2) of Gypsum plasterboard plant

Year	**PP Electricity**						**PP Diesel oil**	**PP Natural gas**	**Total**
	Coal	**Lignite**	**Natural gas**	**Hydro-energy**	**Geothermal + wind +solar**	**Other**			
2021	0.357	0.223	0.442	0.323	0.317	0.048	0.029	14.996	16.736
2022	0.346	0.216	0.428	0.313	0.306	0.047	0.032	15.293	16.979
2023	0.347	0.217	0.429	0.314	0.307	0.047	0.035	15.328	17.023

4.3.4 Total energy footprint

The EF of gypsum plasterboard production was analyzed on a facility basis in the previous sections. As a result of the calculations, the energy footprint of gypsum plasterboard production is determined to be 23.586 MJ/m^2. Examining the total EF reveals that natural gas consumption is the largest source, diesel consumption has the lowest EF contribution. Figure 4.13 shows the EF values for gypsum plasterboard production. The Figure 4.13 shows that the energy required to produce one square meter of gypsum plasterboard increased in 2022. This change is primarily attributed to the impurity levels of the raw materials and the associated crystal water content.

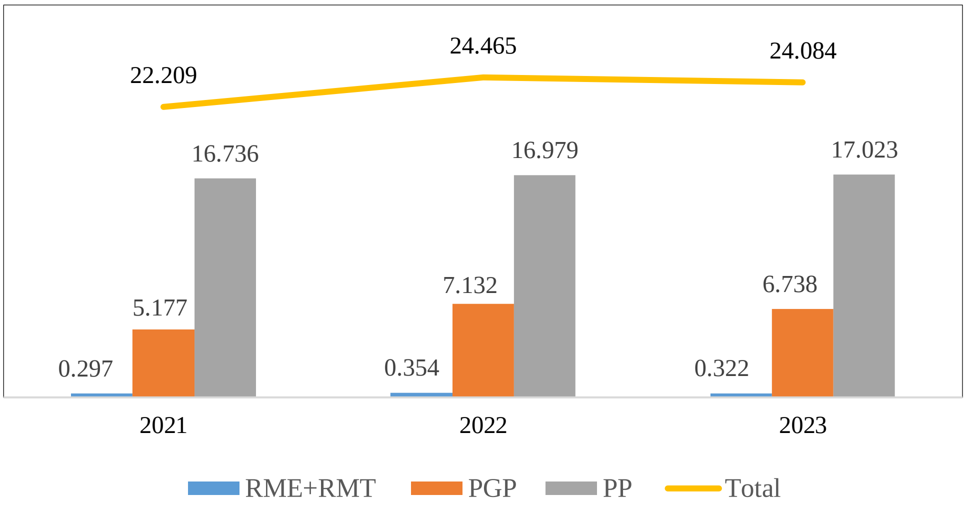

Figure 4.13 Total EF by process and year

The distribution of the total footprint by facility is shown in the Figure 4.14. The PP contributes the most to EF (%71.7) in gypsum plasterboard production, with natural gas being the primary energy source used there. Following this, the PGP accounts for 26.9% of the total footprint. The remaining energy usage is attributed to raw material extraction and transportation.

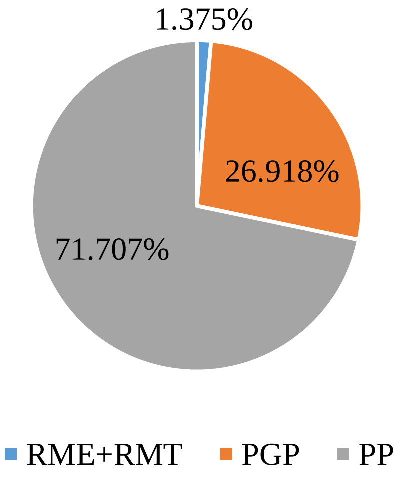

Figure 4.14 EF by facility

The analysis of the colors (Figure 4.15) representing the energy footprint shows that a significant portion of the energy sources used—such as natural gas, coal, and diesel—are fossil-based. Consequently, 96.49% of the energy footprint is classified as black energy. Additionally, 1.65% of the footprint results from hydropower associated with electricity consumption, which is classified as blue energy. The remaining 1.62% is attributed to electricity consumption from sources classified as white, brown, and yellow energy.

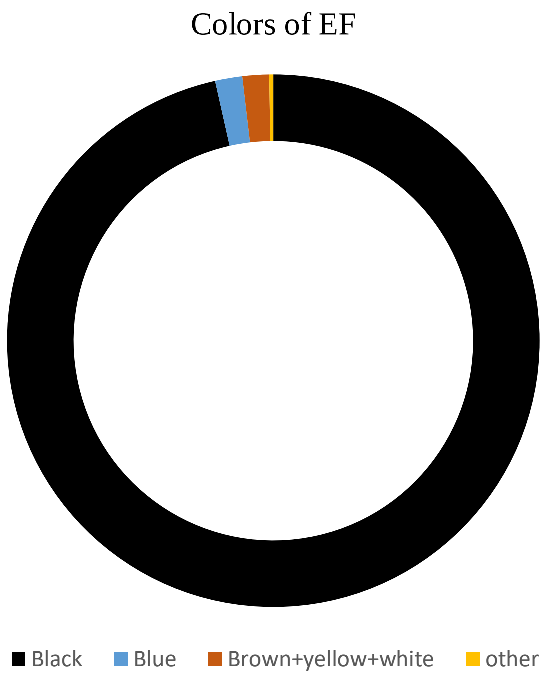

Figure 4.15 Colors of EF

CHAPTER 5
DISCUSSION

The environmental impacts of gypsum plasterboard production from cradle to gate have been conducted under three main headings: water footprint, carbon footprint, and energy footprint.

It is important to acknowledge that this study has certain limitations. The analysis conducted was cradle-to-gate, meaning it only considered the environmental impacts from raw material extraction to the factory gate. For a more comprehensive understanding, a cradle-to-grave analysis should be performed, covering the entire lifecycle from raw material extraction through production, use, and final disposal. This would provide a complete picture of the environmental footprint and identify additional opportunities for reducing impacts across the entire lifecycle.

Another limitation of this study is that the data used were directly obtained from the company and based on invoices and meters. For instance, the electricity consumption data for the gypsum plasterboard plant were aggregated for the entire facility. For a more detailed analysis and to develop strategies aimed at reducing the CF and improving energy efficiency, the consumption of each machine or section should be calculated separately.

In the existing literature, there are relatively few studies that comprehensively analyze the environmental impacts of gypsum plasterboard production, particularly in the context of its carbon, water, and energy footprints. However, the findings of this study align with several key studies that have highlighted the significant carbon emissions associated with natural gas consumption in the calcination process. For instance, Fořt and Černý identified that calcination is the most carbon-intensive process in gypsum production, similar to our findings where natural gas consumption in the calcination process was a major contributor to carbon emissions. Although their research focused on gypsum production, it is important to note that gypsum production is a critical part of the overall plasterboard manufacturing process, thus making their findings highly relevant to our study on gypsum plasterboard production.

Similarly, Giama and Papadopoulos (2015) emphasized the significant CF of building materials during production and transportation stages. Their life cycle analysis revealed CO_2 emissions of 0.39226 t GHG/kg for plasterboard, carbon footprint analysis revealed of 0.0001 t CO_{2eq} /kg which is consistent with the emissions reported in this study.

Lushnikova and Dvorkin (2016) investigated the sustainability of gypsum products and reported an embodied energy of approximately 6.75 MJ/kg for gypsum plasterboard, with a carbon footprint of about 0.38 kg CO_2 per 1 kg. In our study, found the energy footprint to be 2.94 MJ/kg and the carbon footprint to be 0.18 kg CO_2/kg. The lower values of CF in this study could be attributed to several factors, such as the purity of raw materials, the distance between the raw material source and the factory, differences in the production processes, and the types of fuels used. These factors can significantly influence both the energy and carbon footprints, highlighting the importance of optimizing production methods and material sourcing to enhance sustainability.

According to the study of Venta et al, the weighted average energy consumption during the production of gypsum plasterboard has been estimated as 35.5387 MJ/m^2. This value is considerably higher than the 23.586 MJ energy consumption obtained in our study. One reason for this difference can be that the report includes the energy consumption of the paper production and transportation process. Another reason for this difference can be the variations in scope and methodology used in the studies.

A comparison with the study by Jimenez Rivero et al. reveals that they reported carbon emissions of 2.53 kg CO_2 per square meter for gypsum plasterboard production. In contrast, our study reported cradle-to-gate emissions of 1.463 kg CO_2 per square meter. The higher emissions in the other study are attributable to their cradle-to-grave approach, which makes the results compatible with each other.

Overall, the comparison with literature underscores the significant environmental impacts of gypsum plasterboard production, particularly in terms of carbon emissions from natural gas consumption and energy use. The alignment of this study’s findings with existing studies further validates the accuracy and reliability of our results, providing a robust basis for recommending sustainable practices and technologies to mitigate these impacts.

CHAPTER 6
CONCLUSION

The findings of this study highlight the significant environmental impact associated with plasterboard production, particularly concerning water, carbon, and energy footprints. To mitigate these impacts and enhance sustainability within the industry, several recommendations and areas for future research are proposed.

This study found that a large portion of the WF is indirect and originates from energy consumption. Therefore, reducing energy consumption is critical not only for lowering the WF but also for reducing the carbon and energy footprints. Improving energy efficiency should be a crucial step, and utilizing energy sources with a low water footprint, such as wind and solar energy, is essential.

The water used to mix the gypsum into slurry in the gypsum plasterboard plant is subsequently evaporated in the dryers. Implementing a water recovery system in the stack of the gypsum plasterboard plant could allow the recycled water to be reused in the process, thereby reducing the direct WF. Research and development in this area should be pursued.

Reducing carbon emissions is another essential area for improvement. Transitioning to renewable energy sources for electricity needs can substantially lower the CF. Incorporating energy-efficient technologies in the production process, like upgrading to high-efficiency dryers and improving insulation, can also contribute to emission reductions. Exploring the use of alternative fuels with lower carbon content, such as biofuels, can be beneficial.

Another area for future research is the development of advanced monitoring and control systems that can optimize resource usage in real-time. Implementing such technologies can lead to more efficient use of water, energy, and raw materials, thereby reducing the environmental effect.

REFERENCES

[1] World Population Prospects 2019 Highlights. United Nations, Department of Economic and Social Affairs, 2019.

[2] M. M. Mekonnen and A. Y. Hoekstra, “Sustainability: Four billion people facing severe water scarcity,” Science Advances, vol. 2, no. 2, Feb. 2016, doi: 10.1126/sciadv.1500323.

[3] A. Y. Hoekstra, A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen, “The Water Footprint Assessment Manual,” 2011. [Online]. Available: www.earthscan.co.uk

[4] “2019 Global Status Report for Buildings and Construction,” International Energy Agency, 2019.

[5] A. Muratoglu, “Re-defining and conceptualizing the Energy Footprint as a Standalone Indicator,” Istanbul: 14th International Exergy, Energy, and Environment Symposium, Dec. 2023.

[6] Anonymous, “Climate and Climate Change .” Accessed: Jul. 08, 2024. [Online]. Available: https://iklim.gov.tr/sss/temel-kavramlar

[7] R. K. Pachauri, A. Reisinger, L. Bernstein, Intergovernmental Panel on Climate Change. Core Writing Team, and Intergovernmental Panel on Climate Change, Climate change 2007 : synthesis report. 2007.

[8] J. Houghton, “Global warming,” Reports on Progress in Physics, vol. 68, no. 6, pp. 1343–1403, Jun. 2005, doi: 10.1088/0034-4885/68/6/R02.

[9] J. houghton, Y. Ding, Griggs D.J, and M.Nouger, “Climate Change 2001: The Scientific Basis,” 2001.

[10] Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Mitigation of Climate Change. 2022. [Online]. Available: www.ipcc.ch

[11] S. Erdoğan, “Enerji, Çevre ve Sera Gazları,” Cankiri Karatekin Universitesi Iktisadi ve Idari Bilimler Fakultesi Dergisi, pp. 277–303, Jun. 2020, doi: 10.18074/ckuiibfd.670673.

[12] Anonymous, “Climate Change: Atmospheric Carbon Dioxide.” Accessed: Jul. 09, 2024. [Online]. Available: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

[13] S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tenabe, “2006 IPCC guidelines for national greenhouse gas inventories,” 2006.

[14] S. Yaşar, “Endüstriyel Karbon Ayak İzinin Hesaplanması: Çimento Sanayi Örneği,” M.Sc. Thesis, Giresun Üniversitesi, Giresun, 2022.

[15] B. Özlem, “Seçilen Bir Kağıt Fabrikasında Karbon Ayak izi Belirlenmesi,” M.Sc. Thesis, İstanbul Technical University, İstanbul, 2013.

[16] Anonymous, “Overview of Greenhouse Gases.” Accessed: Jul. 09, 2024. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases

[17] Anonymous, “SF6 Kullanımı.” Accessed: Jul. 10, 2024. [Online]. Available: https://www.elder.org.tr/tr/ar-ge-ve-is-gelistirme/uluslararasi-fonlu-projeler/sf6-kullanimi

101#:~:text=SF6%20Gaz%C4%B1%20Nedir%3F,olmak%20%C3%BCzere%20bir%C3%A7ok%20alanda%20kullan%C4%B1lmaktad%C4%B1r.

[18] M. Yeşilyurt, “Hazır Beton Santralinde Karbon Ayak İzinin Değerlendirilmesi,” M.Sc. Thesis, Atatürk Universitesi, Erzurum, 2023.

[19] Anonymous, “Birleşmiş Milletler İklim Değişikliği Çerçeve Sözleşmesi.” Accessed: Jul. 10, 2024. [Online]. Available: https://iklim.gov.tr/bm-iklim-degisikligi-cerceve-sozlesmesi-i-33

[20] Anonymous, “UNFCCC.” Accessed: Jul. 10, 2024. [Online]. Available: https://unfccc.int/

[21] Anonymous, “Kyoto Protocol.” Accessed: Jul. 10, 2024. [Online]. Available: https://unfccc.int/kyoto_protocol

[22] Anonymous, “The Paris Agreement.” Accessed: Jul. 10, 2024. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement

[23] Anonymous, “European Green Deal.” Accessed: Jul. 10, 2024. [Online]. Available:https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[24] J. Fořt and R. Černý, “Carbon footprint analysis of calcined gypsum production in the Czech Republic,” J Clean Prod, vol. 177, pp. 795–802, Mar. 2018, doi: 10.1016/j.jclepro.2018.01.002.

[25] E. Giama and A. M. Papadopoulos, “Assessment tools for the environmental evaluation of concrete, plaster and brick elements production,” J Clean Prod, vol. 99, pp. 75–85, Jul. 2015, doi: 10.1016/j.jclepro.2015.03.006.

[26] T. Schlegel and A. Shtiza, “Environmental footprint study of mortar, render and plaster formulation / Studie über die Umweltauswirkungen von Mörtel,” Mauerwerk, vol. 19, no. 5, pp. 370–382, Oct. 2015, doi: 10.1002/dama.201500676.

[27] N. Lushnikova and L. Dvorkin, “Sustainability of gypsum products as a construction material,” in Sustainability of Construction Materials, Elsevier, 2016, pp. 643–681. doi: 10.1016/b978-0-08-100370-1.00025-1.

[28] ASMI, “An Industry Average Cradle-to-Gate Life Cycle Assessment of 1/2” Lightweight and 5/8” Type X Conventional Gypsum Board for the USA and Canadian Markets,” May 2020. [Online]. Available: http://www.buildgp.com/Georgia-Pacific-Gypsum

[29] G. J. Venta, P. Eng, G. Venta, and C. Ottawa, “Life Cycle Analysis of Gypsum Board and Associated Finishing Products,” 1997.

[30] ASMI, “An Industry Average Cradle-to-Gate Life Cycle Assessment of Glass Mat Gypsum Panels for the USA and Canadian Markets,” Aug. 2016. [Online]. Available: http://www.buildgp.com/Georgia-Pacific-Gypsum

[31] A. Rodrigo-Bravo, L. Alameda Cuenca-Romero, V. Calderón, Rodríguez, and S. Gutiérrez-González, “Comparative Life Cycle Assessment (LCA) between standard gypsum ceiling tile and polyurethane gypsum ceiling tile,” Energy Build, vol. 259, Mar. 2022, doi: 10.1016/j.enbuild.2022.111867.

[32] M. A. Pedreño-Rojas, J. Fořt, R. Černý, and P. Rubio-de-Hita, “Life cycle assessment of natural and recycled gypsum production in the Spanish context,” J Clean Prod, vol. 253, Apr. 2020, doi: 10.1016/j.jclepro.2020.120056.

[33] A. Jiménez Rivero, R. Sathre, and J. García Navarro, “Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union,” Resour Conserv Recycl, vol. 108, pp. 171–181, Mar. 2016, doi: 10.1016/j.resconrec.2016.01.014.

[34] Y. J. Liu, L. Wang, Y. W. Kang, J. R. Fang, and J. Q. Liu, “Facing climate change: Environmental evaluation of gypsum-like CO2utilization Mg-based materials,” in IOP Conference Series: Earth and Environmental Science, IOP Publishing Ltd, Dec. 2020. doi: 10.1088/1755-1315/612/1/012069.

[35] A. Yaras et al., “Characteristics, energy saving and carbon emission reduction potential of gypsum wallboard containing phase change material,” J Energy Storage, vol. 55, Nov. 2022, doi: 10.1016/j.est.2022.105685.

[36] A. H. Buchanan and B. G. Honey, “Energy and carbon dioxide implications of building construction,” 1994.

[37] X. Wang, S. Sun, X. Tian, D. Liu, and F. Zhao, “Development of Environment-Friendly Plastering Gypsum,” in IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Mar. 2019. doi: 10.1088/1757-899X/484/1/012048.

[38] C. Maalouf et al., “An energy and carbon footprint assessment upon the usage of hemp-lime concrete and recycled-PET façades for office facilities in France and Italy,” J Clean Prod, vol. 170, pp. 1640–1653, Jan. 2018, doi: 10.1016/j.jclepro.2016.10.111.

[39] N. Papailiopoulou, H. Grigoropoulou, and M. Founti, “Energy Analysis of the Effects of High-Level Reincorporation of Post-consumer Recycled Gypsum in Plasterboard Manufacturing,” Waste Biomass Valorization, vol. 8, no. 5, pp. 1829–1839, Jul. 2017, doi: 10.1007/s12649-016-9750-7.

[40] M. Bustillo Revuelta, “Gypsum Products,” in Construction Materials Geology, Production and Applications , 2021, pp. 195–215. doi: 10.1007/978-3-030-65207-4_8.

[41] J. Karni and Y. Karni, “Gypsum in construction: origin and properties,” Mater Struct, vol. 28, pp. 92–100, 1995.

[42] C. Pritzel, M. Emami, S. Afflerbach, M. Killian, and R. Trettin, “Formation of α-Hemihydrate Inside of a Gypsum Crystal during the Dehydration Process,” Crystals (Basel), vol. 12, no. 12, Dec. 2022, doi: 10.3390/cryst12121780.

[43] Y. Li and S. Ren, “Gypsum Decorative Materials,” in Building Decorative Materials, Elsevier, 2011, pp. 54–74. doi: 10.1533/9780857092588.54.

[44] X. Li and M. Ran, “Gypsum-Based Humidity-Control Material: Preparation, Performance and Its Impact on Building Energy Consumption,” Materials, vol. 16, no. 15, Aug. 2023, doi: 10.3390/ma16155211.

[45] Anonymous, “Alçı Hakkında Bilgi ve Tarihçesi.” Accessed: May 03, 2024. [Online]. Available: https://www.alcibay.com/tr/kurumsal/alci-hakkinda-bilgi-ve-tarihcesi-7

[46] Anonymous, “Water Footprint Network.” Accessed: Nov. 01, 2023. [Online]. Available: https://www.waterfootprint.org/

[47] M. Wackernagel and W. E. Rees, “Our ecological footprint: reducing human impact on the earth,” New Society Publishers, 1996.

[48] D. Pandey, M. Agrawal, and J. S. Pandey, “Carbon footprint: Current methods of estimation,” Environ Monit Assess, vol. 178, no. 1–4, pp. 135–160, Jul. 2011, doi: 10.1007/s10661-010-1678-y.

[49] T. Wiedmann and J. C. Minx, “A Definition of Carbon Footprint,” 2008. [Online]. Available: https://www.novapublishers.com/catalog/product_info.php?products_id=5999.

[50] Anonymous, “www.footprintnetwork.org,” Global Footprint Network.

[51] J. Ranganathan et al., “The Greenhouse Gas Protocol a Corporate Accounting and Reporting Standard,” 2011.

[52] D. Caro, “Carbon Footprint,” in Encyclopedia of Ecology: Volume 1-4, Second Edition, vol. 4, Elsevier, 2019, pp. 252–257. doi: 10.1016/B978-0-12-409548-9.10752-3.

[53] Jonathan. Loh, World Wildlife Fund., United Nations Environment Programme., and World Conservation Monitoring Centre., Living planet report : 2002. WWF International, 2002.

[54] X. Tian et al., “Energy footprint pathways of China,” Energy, vol. 180, pp. 330–340, Aug. 2019, doi: 10.1016/j.energy.2019.05.103.

[55] “Yearly Distribution of Türkiye’s Gross Electricity Generation by Primary Energy Resources.” Accessed: Jul. 30, 2024. [Online]. Available: https://www.teias.gov.tr/aylik-elektrik-uretim-tuketim-raporlari

[56] M. M. Mekonnen, P. W. Gerbens-Leenes, and A. Y. Hoekstra, “The consumptive water footprint of electricity and heat: A global assessment,” Environ Sci (Camb), vol. 1, no. 3, pp. 285–297, 2015, doi: 10.1039/c5ew00026b.

[57] R. Bosman, “Water Footprint of Widely Used Construction Materials Steel, Cement and Glass,” University of Twente , 2016.

[58] A. Muratoglu, Z. Sakınç, M. I. Yuce, and A. Aytek, “Estimating the Water Footprint of Electricity in Artificial Reservoirs: a Case Study for Atatürk Dam,” in 4 th International Conference on Hydroscience & Engineering, İzmir , 2022.

[59] İ. Alagöz, E. Coşkun, S. Babaoğlu, R. Kaykaç, and A. Cidacı, “EÜAŞ Merkez Kampüs 2021 Yılı Karbon Ayak İzinin Hesaplanması,” 2022.

[60] S. Sawant, “A new method of assessment and equations on Carbon footprint,” IOSR Journal of Applied Geology and Geophysics, vol. 03, no. 04, pp. 52–59, Apr. 2016, doi: 10.9790/0990-03415259.

CURRICULUM VITAE

Name and Surname: Zehra SAKINÇ

Educations:

Degree	University	Department	Year
B.Sc.	Gaziantep University	Civil Engineering	2021
B.Sc.	Gaziantep University	Mechanical Engineering	2021
M.Sc.	Gaziantep University	Civil Engineering - Hydraulics	2024

Experience:

- Intern Site Engineer / Günsev İnşaat / February 2021-June 2021
- R&D Engineer / Fernas Alçı San. Tic. A.Ş. Ar-Ge Merkezi / March 2023-

Publications:

- Z. Sakınç, A. Muratoğlu, and İ. Yüce, “Energy Footprint of Gypsum Plasterboard Production Plant.” 12th International Exergy, Energy and Environment Symposium (IEEES-14), December 24-27, 2023, Tuzla, Istanbul, Türkiye
- Z. Sakınç, A. Muratoğlu, and M. İ. Yüce, “Açık Su Yüzeyinden Buharlaşmanın Alansal Haritalarının Üretilmesi: Şanlıurfa İli.” 11. Ulusal Hidroloji Kongresi 2022, October 13-14, Gaziantep, Türkiye
- Muratoğlu, Z. Sakınç, M. I. Yüce, and A. Aytek, “Estimating the Water Footprint of Electricity in Artificial Reservoirs: A Case Study for Ataturk Dam.” 14th International Conference on Hydro science & Engineering, May 26-27, Izmir, Türkiye