REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

N° Série : ………/2026

Université Kasdi Merbah Ouargla

Faculté des sciences appliquées

Département de Génie Mécanique

THESE

Pour l'obtention du Diplôme de

DOCTORAT ES SCIENCES

Option : Génie Mécanique

Présenté Par :

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-THEME-

Contribution à la récupération d'énergie dans les industries non énergétiques en Algérie.

Soutenue le : 23/ 06 / 2026

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Année universitaire 2025/2026

REPUBLIC OF ALGERIA DEMOCRATIC AND POPULAR
Ministry of Higher Education and Scientific Research

Serial Nº: ………/2026

Kasdi Merbah University Ouargla

Faculty of Applied Sciences

Department of Mechanical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (PhD)

in Mechanical Engineering

by

Robei Sarra

-TITLE-

Contribution to Energy Recovery in Non-Energy Industries in Algeria.

Defended on: 23 / 06 / 2026

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Academic Year: 2025/2026

Abstract

Energy provides an important driver for economic and social development; however, the significant rise in worldwide consumption—over 81% of which in 2023 was met by fossil fuels—has led to increasing pressure on natural resources and the environment. Algeria, as a developing country, is focusing on diversifying its resources and ensuring environmental sustainability through energy and economic policies. This study examines the structural evolution of Algeria's non-energy industries, emphasizing the primary driving factors influencing energy consumption and CO_2 emissions, including industrial scale, activity effect, energy intensity, sectoral structure, and fossil fuel dependency. Using quantitative sectoral data from 2002 to 2021 and Logarithmic Mean Divisia Index (LMDI) decomposition analysis, the study evaluates the influence of non-energy industries on national energy consumption and their environmental effects. The findings show that industrial activity (scale effect) was the dominant driver, contributing to a 527.93% increase in energy consumption, while energy intensity improvements and structural shifts only modestly offset this growth. Similarly, CO_2 emissions from non-energy industries rose from 25.92 Mt in 2006 to 50.60 Mt in 2021, with industrial scale contributing 26.12 Mt of the total increase. Despite Algeria's efforts to diversify its energy mix, targeting 27% of electricity from renewables by 2030, the non-energy industrial sector remains challenged by technological inefficiencies, increasing energy intensity, and persistent reliance on fossil fuels (over 51% of energy from natural gas). The results illustrate the imperative for policy reform, technology advancement, and cleaner production methods. This study applies an integrated analytical framework combining plant conversion measures and alternative mitigation scenarios, such as CO_2-to-methanol conversion, which shows potential to reduce up to 60% of industrial CO_2 emissions (approximately 28.18 Mt annually). The analysis assesses the effectiveness of these strategies using quantitative evaluation and scenario modeling, providing insights to guide evidence-based policy decisions that promote sustainable industrial transformation and low-carbon development in Algeria.

Keywords: Energy consumption; renewable energy; non-energy industry; energy intensity; Algeria.

Résumé

L'énergie est un moteur essentiel du développement économique et social ; toutefois, la forte augmentation de la consommation mondiale dont plus de 81 % a été couverte par les combustibles fossiles en 2023, exerce une pression croissante sur les ressources naturelles et l'environnement. L'Algérie, en tant que pays en développement, s'efforce de diversifier ses ressources et d'assurer la durabilité environnementale à travers des politiques énergétiques et économiques. Cette étude examine l'évolution structurelle des industries non énergétiques algériennes en mettant l'accent sur les principaux facteurs de la demande énergétique et des émissions de CO_2 : l'échelle industrielle, effet activité, l'intensité énergétique, la structure sectorielle et la dépendance aux énergies fossiles. À partir de données sectorielles quantitatives couvrant la période 2002-2021 et en utilisant la méthode de décomposition Logarithmic Mean Divisia Index (LMDI), l'étude évalue l'impact de ces industries sur la consommation nationale d'énergie et leurs effets environnementaux. Les résultats montrent que l'activité industrielle est le moteur dominant, ayant contribué à une augmentation de 527.93 % de la consommation énergétique, tandis que les améliorations d'intensité énergétique et les changements structurels ne compensent que modestement cette croissance. De même, les émissions de CO_2 des industries non énergétiques sont passées de 25.92 Mt en 2006 à 50.60 Mt en 2021, l'échelle industrielle représentant 26.12 Mt de cette hausse. Malgré les efforts d'Algérie pour diversifier son mix énergétique, visant 27 % d'électricité d'origine renouvelable d'ici 2030, le secteur industriel non énergétique reste confronté à des inefficacités technologiques, une intensité énergétique croissante et une dépendance persistante aux combustibles fossiles (plus de 51 % de l'énergie provenant du gaz naturel). Ces résultats soulignent la nécessité de réformes politiques, de progrès technologiques et de méthodes de production plus propres. L'étude applique un cadre analytique intégré combinant des mesures de conversion des usines et des scénarios alternatifs d'atténuation, tels que la conversion du CO_2 en méthanol, qui pourrait réduire jusqu'à 60 % des émissions industrielles de CO_2 (environ 28.18 Mt par an). L'analyse évalue l'efficacité de ces stratégies par une modélisation quantitative et des scénarios prospectifs, fournissant des repères pour orienter des décisions politiques fondées sur des preuves et favoriser une transformation industrielle durable et un développement à faible émission de carbone en Algérie.

Mots clés : Consommation d'énergie ; énergies renouvelables ; industrie non énergétique ; intensité énergétique ; Algérie.

الملخص

تعد الطاقة محركًا أساسيًا للتنمية الاقتصادية والاجتماعية؛ إلا أنّ الارتفاع الحاد في الاستهلاك العالمي — حيث غطّت الوقود الأحفوري أكثر من 81 % من هذا الاستهلاك في عام 2023 — زاد الضغط على الموارد الطبيعية والبيئة. تسعى الجزائر، بوصفها بلدًا ناميًا، إلى تنويع مصادرها وضمان الاستدامة البيئية من خلال سياسات طاقية واقتصادية. تدرس هذه الدراسة التطور الهيكلي للصناعات غير الطاقوية في الجزائر، مع التركيز على العوامل الرئيسة المؤثرة في الطلب على الطاقة وانبعاثات ثاني أوكسيد الكربون، وهي: الحجم الصناعي (تأثير النشاط)، كثافة الطاقة، الهيكل القطاعي، والاعتماد على الوقود الأحفوري. باستخدام بيانات قطاعية كمية للفترة 2002-2021 وتحليل التحلل باستخدام مؤشر لغاريتميك مين ديفيزيا (LMDI)، تُقيّم الدراسة أثر هذه الصناعات على الاستهلاك الوطني للطاقة وآثارها البيئية. أظهرت النتائج أن النشاط الصناعي (تأثير الحجم) هو المحرك الرئيس، حيث ساهم بزيادة قدرها 527.93 % في استهلاك الطاقة، بينما لم تُحدث تحسينات كثافة الطاقة والتحولات الهيكلية سوى تخفيف محدود لهذا النمو. كذلك، ارتفعت انبعاثات CO_2 من الصناعات غير الطاقوية من 25.92 مليون طن في 2006 إلى 50.60 مليون طن في 2021، وكان للحجم الصناعي نصيب 26.12 مليون طن من هذا الارتفاع. رغم جهود الجزائر لتنويع مزيجها الطاقي — باستهداف 27 % من الكهرباء من مصادر متجددة بحلول 2030 — يظل القطاع الصناعي غير الطاقوي يواجه تحديات تمثلت في عدم كفاءة التقنيات، ارتفاع كثافة الطاقة، والاعتماد المستمر على الوقود الأحفوري (أكثر من 51 % من الطاقة تأتي من الغاز الطبيعي). تُظهر النتائج ضرورة إصلاح السياسات، تطوير التكنولوجيا، واعتماد طرق إنتاج أنظف. تطبق الدراسة إطارًا تحليليًا متكاملاً يجمع بين تدابير تحويل المصانع وسيناريوهات تخفيف بديلة، مثل تحويل CO_2 إلى ميثانول، والذي يُظهر إمكانية تقليل ما يصل إلى 60 % من الانبعاثات الصناعية (حوالي 28.18 مليون طن سنويًا). تُقيّم التحليلات فعالية هذه الاستراتيجيات باستخدام التقييم الكمي والنمذجة بالسيناريوهات، لتقديم رؤى تُوجّه اتخاذ القرارات السياسية المبنية على أدلة وتُعزز التحول الصناعي المستدام والتنمية منخفضة الكربون في الجزائر.

الكلمات مفتاحية:

استهلاك الطاقة؛ الطاقة المتجددة؛ الصناعة غير المرتبطة بالطاقة؛ كثافة الطاقة؛ الجزائر.

Acknowledgments

First and foremost, I wish to express my profound and humble gratitude to ALLAH, the Almighty, whose divine guidance, strength, and blessings have sustained me throughout the entirety of this academic journey and enabled the completion of this thesis.

I am honored to extend my sincere appreciation to my supervisor, *Prof. Noureddine Settou*, for his exemplary academic guidance, insightful observations, constructive critiques, and continual encouragement have been instrumental in shaping the quality and direction of this research.

I am also deeply indebted to the members of the examination committee, whose time, expertise, and critical evaluation have significantly contributed to the refinement and quality of this work.

My appreciation is further extended to all individuals and institutions whose support, assistance, or contributions, in any capacity, facilitated the progress and realization of this study.

Dedication

To my wonderful parents, whose unconditional love and unwavering support have been my greatest source of strength.

To my dear brothers and sisters, who are my lifelong companions.

To my precious niblings, my little birds, who bring endless joy.

To my cherished friends, whose kindness, encouragement, and belief in me never faltered,

I dedicate this work with love and gratitude.

Table of contents

Chapter 04 CO_2 Emissions in Algeria's Non-energy Industries: Trends, Key Drivers, and Mitigation Strategies

Chapter 05 CO_2 Emissions Conversion to Methanol Strategy: Addressing Non-energy Industrial Emissions in Algeria

Nomenclature

Symbols

$X_{n,i}$	Factor influencing the change in energy consumption
ΔE_{tot}	Total energy intensity index from year 0 to year *t*
ΔE_{act}	Additive activity effect [ktoe]
ΔE_{str}	Additive structural effect [ktoe]
ΔE_{int}	Additive intensity effect [ktoe]
S_i	Production share
I_i	Energy intensity
Q	Value added of the non-energy industry output at 1989 constant prices (billion AD)
E	Total energy consumption [ktoe]
D_{tot}	Total multiplicative factor decomposition
D_{act}	Multiplicative activity effect
D_{srt}	Multiplicative structural effect
D_{int}	Multiplicative intensity effect
Eco_2	Total emission of carbon dioxide
E_{ij}	Energy consumption of the i sub-sector based on fuel type j
EF_j	CO_2 emission factor of the j fuel type
X_t	Observation at time t
ϵ_t	White noise (error term)
β_i, α_i	Weight vectors
∇X_t	First-order differencing
e_{ij}	Energy structure of i sub-sector based on j source of energy (ktoe)
R	CO_2 emissions coefficient of energy j consumed by sub-sector i
ΔC_{idscl}	Industrial scale effect
ΔC_{idstr}	Industrial structure effect
ΔC_{eint}	Energy intensity effect
ΔC_{estr}	Energy structure effect
ΔC_{cec}	Carbon emission coefficient effect

η_{idscl}	Contribution ratio of industrial scale
η_{idstr}	Contribution ratio of industrial structure
η_{eint}	Contribution ratio of energy intensity
η_{estr}	Contribution ratio of energy structure
η_{cec}	Contribution ratio of emission factor

Abbreviation

AF	Food products, beverages and tobacco
AI	Artificial intelligence
ARIMA	Autoregressive integrated moving average
BP	Back propagation
BTP	Construction and public works
CBI	Community-based initiatives
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CE	Construction materials
CEREFE	Commission for Renewable Energies and Energy Efficiency
CI	Chemistry
CSP	Concentrated solar power
DRM	Dry-air reforming of methane
ECRCM	Electrochemical reduction of CO_2 to methanol
EFP	Ecological footprint
EI	Energy institute
ETS	Emissions trading systems
FAO	Food and Agriculture Organization
FDI	Foreign direct investment.
GHG	Greenhouse gas
GM	Grey model
IEA	International energy agency
IS	Iron and steel, mechanical, electronic and electric equipment

ITCL	Textile, clothing and leather
LMDI	Logarithmic Mean Divisia Index
LSTM	Long short-term memory
MAPE	Mean absolute percentage error
MEM	Ministry of Energy and Mining
MENA	Middle East and North Africa countries
Mtoe	Million tons of oil equivalent
OI	Other industries
SME	Small and medium-sized enterprises
SVR	Support Vector regression
WST	Water saving technologies

List of figures

List of tables

Global Introduction

Global Introduction

The global energy landscape is characterized by a significant reliance on fossil fuels. In 2023, world energy demand increased by 2%, with over 81% of this growth met by oil, natural gas, and coal, while renewables accounted for the remaining 19% [1]. Proven oil reserves were estimated at 1760 billion barrels at the end of 2022, representing approximately 52.5 years of production at current rates, assuming new discoveries. OPEC countries hold over three-quarters of global oil reserves and contribute more than 45% of production [2]. Oil demand grew by 1.6%, more than double the annual average over the past decade, driven by the transport and petrochemical sectors. Natural gas consumption increased by 3%, and fossil fuels accounted for 3.1% growth in electricity generation, with India and China contributing 70% of this global growth [1].

The combustion of fossil fuels is the principal source of anthropogenic greenhouse gas emissions, particularly carbon dioxide, which drives global climate change. To avoid the most devastating effects of climate change, the world must implement an urgent and decisive change to a low-carbon economy. This change requires a two-pronged strategy; first, an overall progress to renewable and clean energy sources, and second, a relentless pursuit of energy efficiency throughout all sectors of the economy. The International Energy Agency (IEA) identifies energy efficiency as the cleanest way to meet energy demands, reduce emissions, and improve energy security. According to IEA, global energy consumption is more than doubled between 1971 and 2019, while CO_2 emissions followed a similar pattern [3]. The increase was mainly attributed to industrialization and urbanization in developing countries.

In 2022, North African countries like Algeria, Egypt, and Libya showed the highest energy supply levels due to abundant fossil fuel resources and developed infrastructure. In contrast, most sub-Saharan African nations, except for South Africa and Nigeria, faced energy poverty and inadequate infrastructure. Algeria is a major producer of oil and unconventional hydrocarbons [4], possessing an estimated 4400 Gbbl of shale gas. Its primary energy resources are natural gas (66%) and crude oil (24%), making it the leading natural gas producer and second-largest oil producer in Africa [2]. This reliance on hydrocarbons highlights a limited diversification of its energy mix.

The Algeria's energy production has consistently grown, primarily driven by natural gas output, highlighting Algeria's dependence on hydrocarbons and limited energy mix diversification. Algeria's strategic plan aims to position the country as a key player in power generation using solar and wind energy, complemented by biomass, cogeneration, and geothermal energy. The concentrated solar power is expected to play a significant role from 2021 onwards [5]. By 2030, renewable energy is projected to contribute 37% of the total installed capacity and 27% of national power generation. The deployment plan includes two phases: Phase 1 (2015-2020) saw an estimated 4010 MW installed, mainly from photovoltaic and wind sources, while Phase 2 (2021-2030) focuses on large-scale renewable energy integration and making CSP economically viable [5].

The industrial sector constitutes 37% of worldwide final energy consumption and plays a substantial role in greenhouse gas emissions, particularly through energy-intensive subsectors like iron and steel, cement, and chemicals [6-8]. Algeria's industrial structure is largely dominated by the hydrocarbons sector. Non-Energy Industries, such as construction materials, iron and steel, chemistry, food products, textiles, and others, are crucial for economic diversification and employment. Algeria's total energy consumption reached 67.2 million tons of oil equivalent (Mtoe) in 2021, a significant increase from 1976. The non-energy industry is the third most energy-intensive sector after transport and households [9]. In 2021, 'households and others' accounted for 46.70% of energy consumption, while the transport sector showed a peak with 14.52 Mtoe, driven by an expanding national automobile fleet [9]. The non-energy sector's consumption rose from 1.8 Mtoe in 1976 to 12.22 Mtoe in 2021 [10].

Despite the growing CO_2 emissions and energy challenges, previous studies have not adequately investigated energy consumption within Algeria's non-energy industrial sector, specifically in areas like 'construction materials' and 'textile, clothing, and leather' industries, highlighting an urgent need for research. While decomposition analysis has been widely applied to energy consumption and CO_2 emissions globally, its application to the

Algerian economy remains limited [10-12]. This thesis is dedicated to addressing this critical gap. Its central aim is to develop a comprehensive framework for the systematic assessment and prioritization of energy recovery opportunities within Algeria's non-energy industrial sectors. To achieve this aim, the research is guided by the following primary objectives:

1- To establish a detailed understanding of the global and national energy context, including Algeria's energy profile, consumption trends, and policy landscape.
2- To analyze the structure, evolution, and energy consumption patterns of Algeria's non-energy industrial sectors to identify key areas of inefficiency.
3- To decompose the drivers of energy consumption and CO_2 emissions within these sectors to understand the underlying factors behind their energy use.
4- To propose a robust decision-support framework and actionable strategies for implementing energy recovery technologies, thereby contributing to industrial decarbonization and enhanced sustainability.

These objectives are operationalized through the following core research questions:

1) What are the principal drivers (e.g., industrial growth, structural change, energy intensity) behind the historical trends in energy consumption and CO_2 emissions within Algeria's non-energy industries?
2) What is the potential of energy recovery within key Algerian non-energy industrial sub-sectors?
3) What integrated policy, technical, and financial strategies are needed to overcome barriers and accelerate the adoption of energy recovery systems in Algeria?

This research employs a mixed-methods approach, combining quantitative and qualitative analysis to build a holistic and evidence-based argument. The methodological framework is designed to move from a macro-level understanding to a micro-level, applied analysis.

The initial phase involves a comprehensive review of secondary data from international and national sources. This includes reports from the International Energy Agency (IEA), BP Statistical Review, Algerian Ministry of Energy and Mines (MEM), Sonatrach, and the

National Office of Statistics (ONS). This data is used to establish trends in energy production, consumption, and economic indicators over a 20-year period .

A core analytical tool used in this thesis is the Logarithmic Mean Divisia Index (LMDI) method. This sophisticated index decomposition analysis technique is applied to time-series data to dissect the changes in aggregate energy consumption and CO_2 emissions into their constituent driving effects. This method allows for a precise quantification of the impact of each driver, providing invaluable insights for policymakers.

For assessing mitigation strategies, the research employs scenario analysis. This involves creating plausible future pathways based on different assumptions (e.g., CO_2 to methanol conversion scenario). This thesis makes several significant and original contributions to knowledge and practice. It provides the first comprehensive LMDI decomposition analysis of energy consumption and CO_2 emissions specifically for Algeria's non-energy industrial sectors, offering unprecedented insight into the dynamics of their environmental impact.

The thesis moves beyond analysis to synthesis, proposing a practical framework to guide industrial managers and policymakers in evaluating and prioritizing energy recovery investments. The findings yield tailored recommendations for Algerian energy and industrial policy, which can serve as a model for other resource-rich economies in North Africa and the Middle East facing similar challenges. The research sits at the intersection of energy economics, industrial engineering, and environmental policy, demonstrating how an integrated approach is necessary to tackle complex sustainability challenges.

This thesis is structured into five chapters, each addressing critical aspects of energy consumption, emissions, and recovery potential in Algeria’s industrial scenario:

Chapter 1 provides a comprehensive overview of the worldwide and Algerian energy landscape, highlighting the current energy consumption patterns, sources, and the implications of energy policies on both local and global scales. The analysis also considers various types of energy resources, with an emphasis on their environmental impacts. The analysis also considers different forms of energy resources, with an emphasis on their environmental impact. Conventional energy sources are evaluated deeply for the demands they place on ecosystems, while alternative options are investigated for the potential to mitigate these effects. The emphasis then moves to Algeria, including a comprehensive analysis of its hydrocarbon reserves, energy production and consumption trends, and the strategic framework of its national energy policy, which encompasses ambitious renewable energy objectives. It finishes by highlighting the importance of the non-energy industrial sector and the issue of energy waste, therefore validating the research's objective.

Chapter 2 provides a detailed economic and historical profile of Algeria's non-energy industrial sector. It traces the sector's evolution from the colonial era through post-independence nationalization, economic liberalization in the 1990s, and contemporary diversification efforts. It breaks down the sector into its key components (e.g., construction materials, chemicals, food products) and analyzes their relative contribution to GDP, employment, and energy consumption. This chapter establishes the "who" and the "what" that will be analyzed in subsequent chapters.

Chapter 3 presents a detailed quantitative analysis of energy consumption trends within the non-energy sector from 2002 to 2021. Using the LMDI decomposition method, it isolates and quantifies the effects of industrial activity, structural change, and energy intensity on overall consumption. The chapter answers the question: Is the sector becoming more or less efficient, and what is driving changes in its energy demand? The results identify the most energy-intensive sub-sectors and trends, pinpointing priority areas for intervention.

Chapter 4 applies the additive LMDI decomposition analysis to the sector's CO_2 emissions. It quantifies the contribution of each driver to the emissions profile. Furthermore, it explores specific mitigation strategies, including a detailed scenario analysis of innovative pathways such as converting captured CO_2 emissions into methanol, assessing both the technical potential and the challenges of such an approach.

Chapter 05 aims to model and forecast a scenario for converting CO_2 to methanol to decrease the impact of CO_2 emissions from non-energy industries in Algeria. The recommended CO_2-to-methanol conversion method offers an efficient technique to reduce emissions and provide an alternative energy source. Scenario analysis and ARIMA forecasts validate its significant mitigation potential, emphasizing the need for combined technologies and supportive policies to achieve Algeria's low-carbon transition and meet global climate goals.

Finally, the thesis concludes by summarizing the important contributions produced during the doctoral research, as well as giving the findings' views and implications.

Chapter 01

Worldwide and Algerian Energy Overview

1.1 Introduction

Every facet of existence depends on energy, which is essential for economic development. Nonetheless, the ecosystem is experiencing significant strain due to a sharp rise in energy consumption. This chapter covers global energy and the Algerian energy overview, analyzing various energy resources and their environmental impact. It also elaborates on the diverse potentials of Algeria's national renewable energy resources.

1.2 Worldwide energy overview

According to the International Energy Agency [3], the total proven oil reserves are estimated at the end of 2022 at 1760 billion barrels. This would represent globally 52.5 years of production as long as the production retains its current rate and those significant new deposits are being discovered. Countries of OPEC owns more than three quarters of the world's oil reserves and provide more than 45% of production [2].

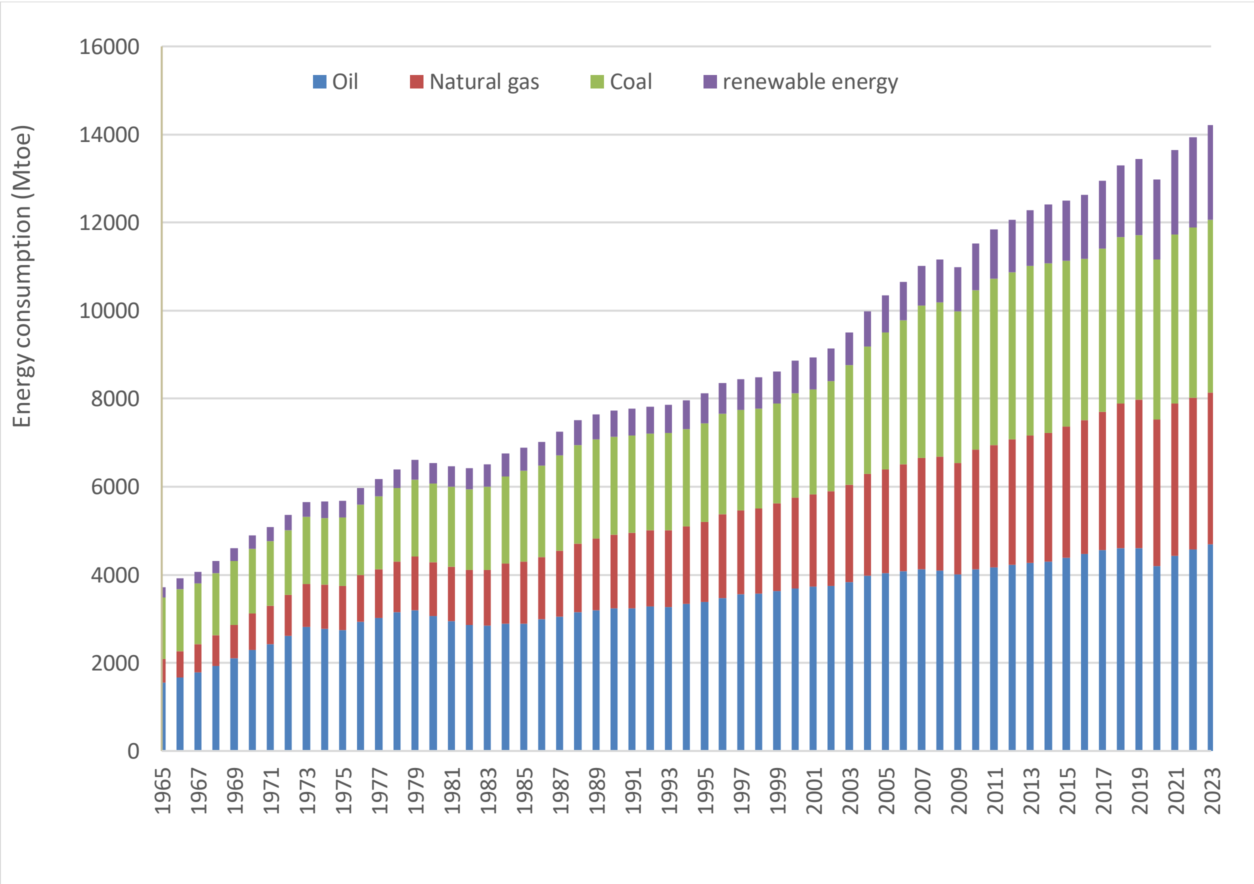

Figure 1.1 world energy consumption by fuel.

World energy demand increased by 2% in 2023, twice more than the level of 2022, driven by the strong growth of global economic [13]. The Energy Institute (EI) declared, that more than 81% of global energy demand growth has been met by oil, natural gas and coal, while renewable sources have met the remaining 19% (figure 1.1). In addition, it concluded that the oil demand has grown by 1.6%, more than twice the annual average rate over the past decade, stimulated by the transport and petrochemical sectors. Furthermore, natural gas consumption has increased by 3%. The largest share of fossil fuels electricity generation has grown with 3.1%, significantly faster in global energy demand, and India and China together accounted for 70% of global growth.

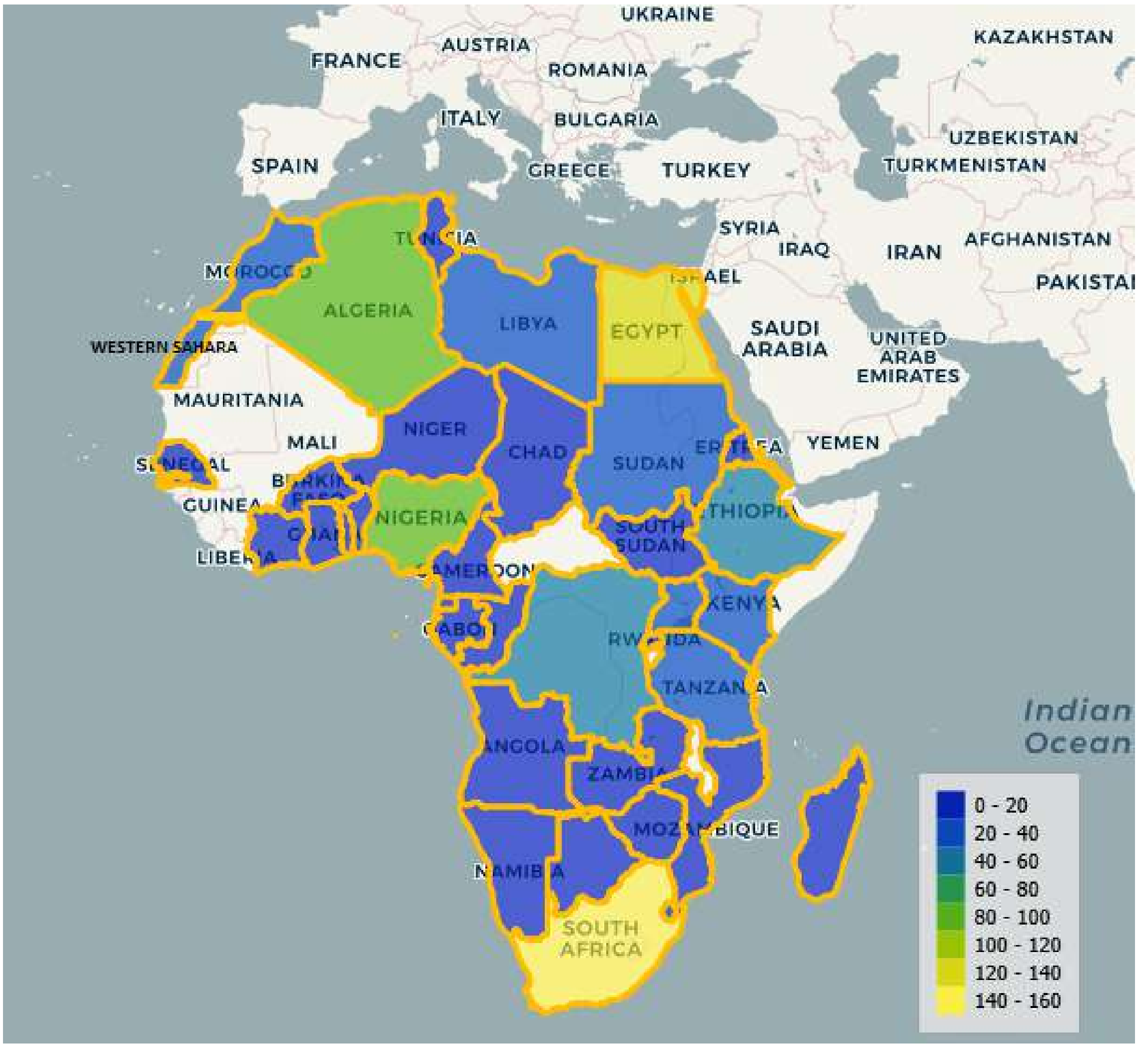

Figure 1.2 Energy supply in Africa by country measured in million tons of oil equivalent (Mtoe), 2022.

Figure 1.2 illustrates the energy supply across African countries in 2022, measured in million tons of oil equivalent (Mtoe) [1]. It indicates significant regional variations, with North

African countries such as Algeria, Egypt, and Libya displaying the greatest energy supply levels owing to their extensive fossil fuel resources and advanced infrastructure. Conversely, the majority of sub-Saharan African nations, especially in East and Central Africa, fall within the lowest supply range, emphasizing energy poverty and inadequate infrastructure. Exceptions like South Africa and Nigeria, which exhibit moderate to high energy supply, indicate their industrialization and resource abundance. The map highlights the relationship between energy availability and economic development, while emphasizing the immediate necessity for focused policies and investments to tackle energy disparity, especially in sub-Saharan Africa.

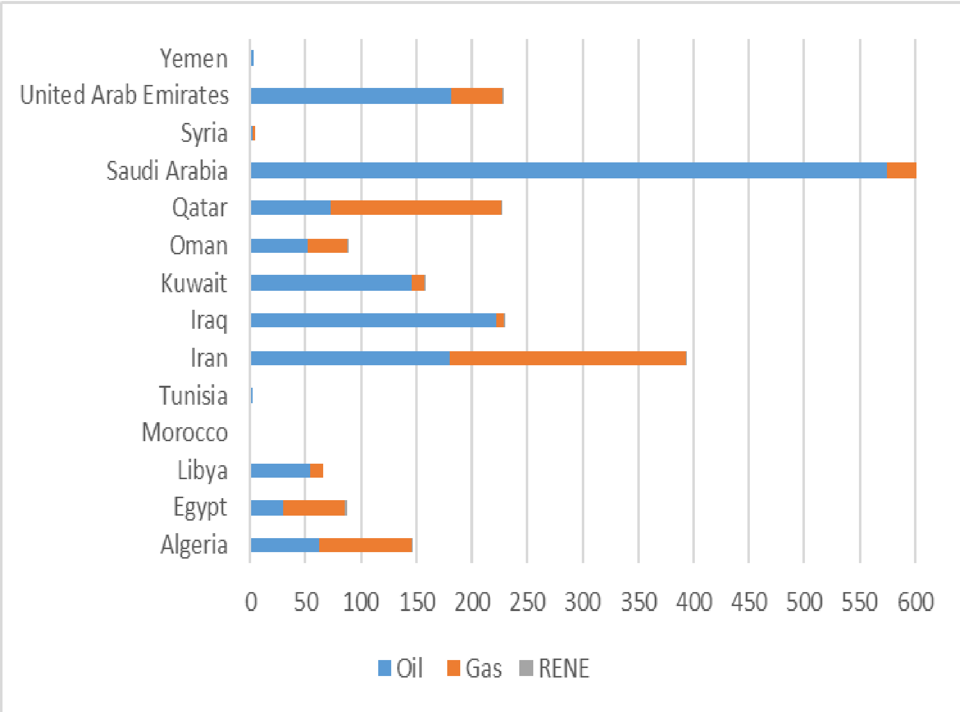

Figure 1.3 Energy production in MENA countries by Mtoe, 2022.

Figure 1.3 depicts energy production in MENA countries for 2022, quantified in million tons of oil equivalent (Mtoe), and categorized into oil, natural gas, and renewable energy sources [1]. The results indicate significant international variations in the magnitude and composition of energy production. Saudi Arabia is the predominant producer in the region, with oil output estimated at over 574 Mtoe. Iran possesses over 180 Mtoe of oil and 213 Mtoe of natural gas, establishing it as the predominant gas producer in the region. Iraq demonstrates substantial hydrocarbon output, 221 Mtoe of oil and 8 Mtoe of gas. Other significant producers comprise the United Arab Emirates, which produces over 181 Mtoe of oil and 46 Mtoe of gas, and

Kuwait, which yields 145 Mtoe of oil and 11 Mtoe of gas. Qatar's output is predominantly gas-focused, yielding about 153 Mtoe of gas and 73 Mtoe of oil.

The development of renewable energy in the region remains limited. Egypt exhibits the greatest contribution with 2 Mtoe, succeeded by Iran (1.37 Mtoe). In the remaining countries, renewable generation does not surpass 1 Mtoe, highlighting the relatively limited contribution of low-carbon energy sources.

1.3 Algerian energy overview

Algeria, as one of the leading producers of oil and unconventional hydrocarbons, possesses an estimated 598.4 Mtoe of shale gas and significantly contributes to global oil and natural gas production, supplying 175.9 Mtoe of energy annually [14]. The primary energy resources of the country consist of natural gas (66%) and crude oil (24%), with gas and oil reserves reaching 1971 Mtoe and 1669 Mtoe, respectively. This positions Algeria as the leading natural gas producer at 105.64 Mtoe annually and the second-largest oil producer in Africa, following Nigeria [1].

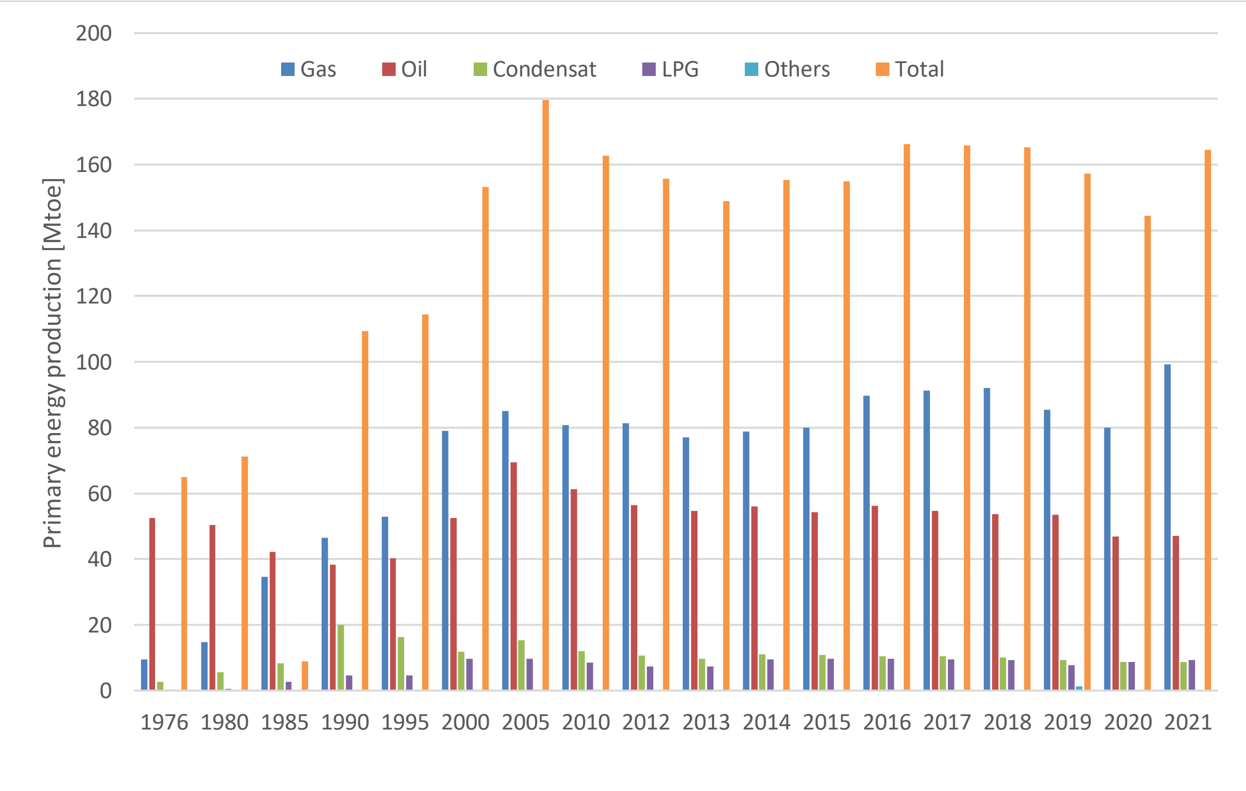

Figure 1.4 Algerian energy production by fuel from 1976 to 2021.

Figure 1.4 illustrates Algeria's primary energy production by fuel type (gas, oil, condensate, LPG, and others) and total energy production from 1976 to 2021[9]. It indicates a consistent growth in overall energy production, predominantly driven by a rise in natural gas output, which becomes the primary energy source during the entire period. Oil production was stable with minor changes, whilst condensate and LPG production demonstrated modest yet consistent rise. The "others" group made a negligible contribution relative to the primary fuels. It underscores Algeria's dependence on hydrocarbons for energy generation, indicating its status as a prominent worldwide energy producer. These developments highlight the nation's reliance on fossil fuels and the restricted diversification of its energy mix.

1.3.1 Algeria’s potential for renewable energy

The figure 1.3 indicates that oil and gas dominate the fossil fuel MENA countries, creating a marked imbalance when compared with the relatively small share of renewable energy sources. This difference suggests an economy affected by fluctuations in global fossil fuel markets, while highlighting an economy able to policies designed to promote a more diversified energy portfolio. It emphasizes a critical transition challenge, with Algeria's imperative to engage in renewable energy development to reduce its dependence on nonrenewable resources.

Algeria's renewable energy program represents a strategic plan aiming at positioning the country as a key participant in power generation, mainly through solar and wind energy, while integrating additional sources such as biomass, cogeneration, and geothermal energy. From 2021, the concentrated solar power (CSP) is projected to enhance these efforts. The implementation of these renewable energy technologies is envisioned as a fundamental driver of sustainable economic growth, fostering a shift toward a more robust and diversified energy sector.

The forecasts show that by 2030 [5], renewable energy will contribute 37% of the total installed capacity and account for 27% of the power generated for national consumption. This considerable ratio emphasizes Algeria’s determination to decrease dependence on fossil fuels while exploiting its substantial renewable energy potential. Based on the solar energy dominates the country’s renewable resource investments, it is considered as both a significant potential and a driver for economic and social development. The predicted rise of solar infrastructure is expected to encourage industrial growth, enhance energy security, and offer Algeria’s renewable energy plan remains broad, embracing wind energy, biomass, geothermal energy, and cogeneration. The implementation of wind agriculture, alongside experimental initiatives in biomass and geothermal energy, reflects a higher commitment to exploring alternative energy pathways to achieve a balanced and sustainable transition.

The renewable energy deployment plan is divided into two separate phases. During the first phase (2015–2020), an estimated 4010 MW of capacity was constructed, mostly from photovoltaic and wind power sources, with 515 MW from biomass, cogeneration, and geothermal energy. The second phase (2021–2030) focuses on large-scale renewable energy integration, helped by the growth of electrical linkages between the northern regions and the Sahara, particularly in Adrar. This infrastructural development is expected to support the deployment of large-scale renewable energy plants in strategic places such as In Salah, Adrar, Timimoune, and Béchar, ultimately boosting the national grid. Moreover, by this period, concentrated solar power is predicted to become commercially viable, substantially broadening the country's renewable energy mix.

The driver of Algeria's renewable energy strategy demonstrates the country's involvement to integrate sustainable energy solutions into its national energy framework. However, the successful realization of this initiative would depend on various aspects, including technological improvements, regulatory frameworks, financial investment, and international collaboration.

1.3.1.1 Solar energy potential

Algeria has been endowed with a strong solar resource for several million years and possesses solar technology expertise allowing development of solar energy use for urban electricity supply, and hydrogen production. Given the climatic conditions, existing but still underexploited investments in current desalination units, high energy costs in areas where regular water supply is not assured, as well as a socio-political environment that is made by a diversely populated coastal area, implementation of solar-powered desalination systems seems a promising method of significant positive impact [15].

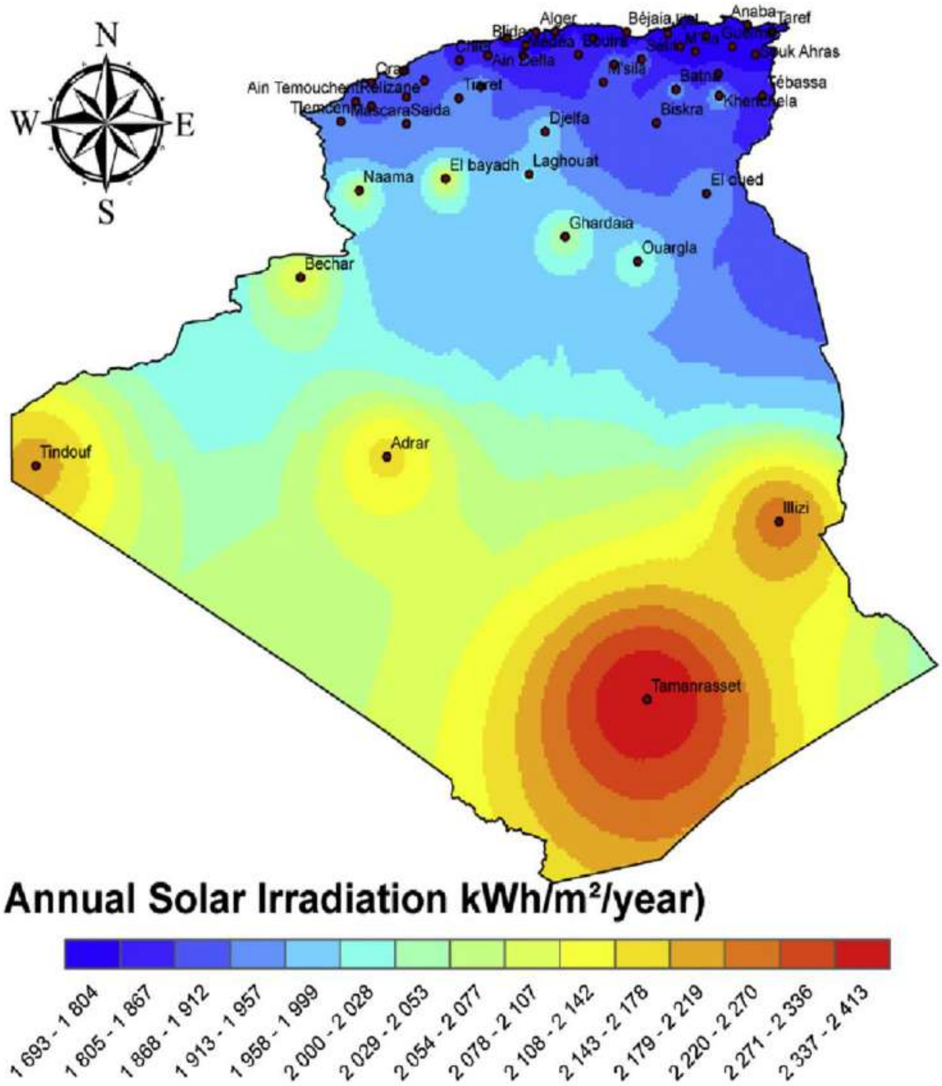

Figure 1.5 Annual average of Algeria's solar irradiation [17].

The southern regions stand out as the most promising areas for utilizing solar energy in hydrogen production, as shown in figure 1.5. Among them, Tamanrasset and Illizi boast exceptional solar potential, receiving approximately 2.4 and 2.2 MWh/m² of annual solar energy, respectively [16]. According to the Commission for Renewable Energies and Energy Efficiency (CEREFE) [5], the national installed renewable energy capacity reached 600.9 MW at the end of 2023, comprising 472 MW. Solar photovoltaic (PV) installations have risen over the past three years, indicating that solar kits totaling 23.06 MW represent over half (48.2%) of the off-grid solar PV capacity. The total installed renewable energy capacity will exceed 4000 MW, including the Ghar Djebilet project with a total capacity of 3200 MW, alongside other projects in progress. Algeria's renewable energy production capacity is anticipated to surpass 4000 MW, mostly owing to the proposed establishment of 21 photovoltaic power plants.

The "2000 MW" project initiative entails the establishment of 15 solar photovoltaic power facilities distributed over 12 wilayas, with individual capacities varying from 80 MW to 220 MW. The "Solar 1000 MW" project comprises five solar photovoltaic power facilities, each with capacities ranging from 50 MW to 300 MW, located across five provinces. The MEM, via Sonelgaz, initiated another EPC tender for the establishment of a 200 MW solar photovoltaic plant with energy storage in the Gara Djebilet region Tindouf to facilitate the ongoing iron ore mining activity.

Furthermore, three hybrid solar power plants, possessing a cumulative capacity of 22 MW, are now under development. These include of an 8 MW facility in Talmine (Adrar), a 3 MW facility in Tabelbala (Béchar), and an 11 MW facility in Tindouf. At the end of December 2023, the national installed renewable energy capacity reached 600.9 MW, with 417.64 MW owned by the MEM, accounting for 98.4% of total grid-connected renewable energy installations and 88.5% of non-hydropower renewable energy capacity.

Between 2020 and 2023, MEM augmented its capacity by 28 MW, constituting 44.6% of the total renewable energy capacity installed in Algeria during this timeframe (62.8 MW), and reflecting a 7.2% increase relative to the cumulative installed capacity at the end of 2019 (389.64 MW). The legislative support for more open system to ensure competition has brought with it high expectations for renewables, focus on solar electric technologies has emerged. Within this fast-growing sector, cost-effectiveness and accelerated implementation is sought in areas of large-scale deployment. As Algeria’s approach is becoming increasingly complex it has attracted both national and foreign investment as well as interest from financiers and investors. With more than five years of experience in implementing solar parks it has built an invaluable reservoir of skills amongst locals. The policy mix is mutually reinforcing and clear national targets, entailing renewable energy generation and technology acquisition, are coupled with energy-export as a complementary objective. If carried out properly, this mix has far-reaching consequences and would make Algeria an emerging solar technological and industrial hub in the Mediterranean.

1.3.1.2 Wind potential

Algeria experiences moderate wind speeds ranging from 2 to 6 m/s (see figure 1.6). This level of wind energy is particularly well-suited for water pumping applications, especially in the Highlands. In Algeria, the first attempt to connect wind turbines to the electrical distribution network dates back to 1957, with the installation of a 100 kW aerogenerator at the Grand Vent site in Algiers. This marked the beginning of Algeria’s exploration into wind energy as a potential source of electricity.

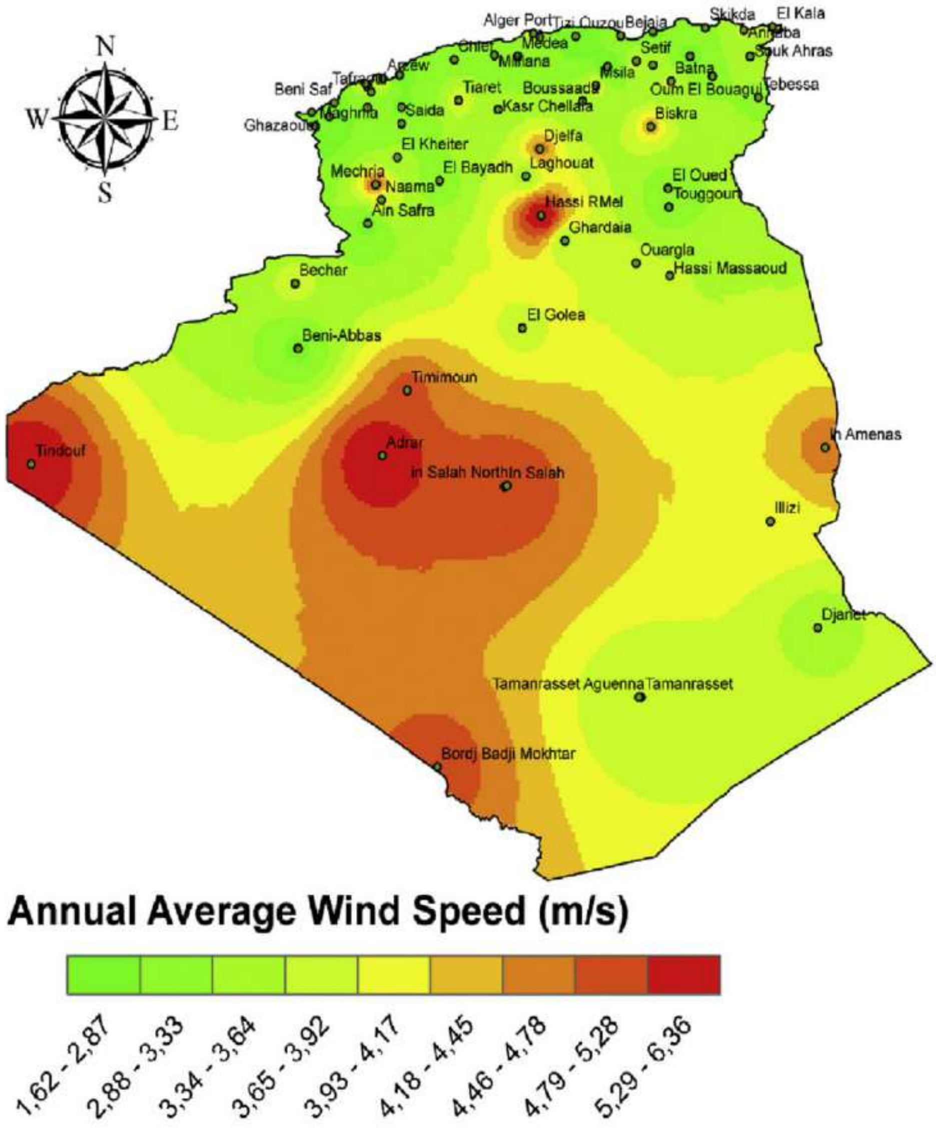

Figure 1.6 Annual average of wind speed in Algeria [17].

The largest wind-powered pumping turbine was installed in 1953 in Adrar by the colonization and hydraulics authorities [15]. This three-bladed machine, featuring a rotor diameter of 15 meters and mounted on a 25-meter-high mast (figure 1.7), operated successfully for nearly a decade. Its installation marked a significant milestone in the early use of wind energy for mechanical applications, particularly in remote and arid regions where access to conventional energy sources was limited. The longevity of its operation, spanning approximately 10 years, underscores the robustness and reliability of this early wind energy technology, despite the limited technological advancements available at the time. This example highlights the potential of wind energy as a sustainable solution for water pumping and other mechanical needs, even in challenging environments.

Following this initial effort, numerous smaller-capacity aerogenerators were installed in various locations across the country. These installations were primarily aimed at providing power to isolated communities and hard-to-access areas, such as telecommunication relay stations. However, the technology of wind turbines was still in its infancy during this period, and as a result, these early experiments were not always successful. It is important to note that this lack of success was not unique to Algeria but was a common challenge faced internationally during the early stages of wind energy development. The global landscape of wind energy began to shift significantly after the first oil crisis, which prompted substantial investments in research and development for wind turbine technology. This period of increased funding and innovation led to remarkable advancements in the efficiency, reliability, and scale of wind turbines. By the late 1980s, wind energy had gained considerable momentum as a viable source of electricity generation.

Modern wind turbines have since become increasingly sophisticated, with significant improvements in their performance and size. The saturation of viable onshore sites with high wind potential has led to the development of Low Wind turbines in recent years. These turbines are specifically designed for areas with lower wind speeds and feature taller towers, larger blades, and smaller electric generators. This innovation reflects the industry’s efforts to maximize the potential of wind energy in less optimal conditions and expand its applicability to a broader range of geographic locations. Globally, the total installed wind power capacity has experienced exponential growth, rising from approximately 6 GW in 1996 to 336 GW by June 2014. This growth underscores the increasing importance of wind energy as a key component of the global renewable energy portfolio.

Figure 1.7 The largest wind-powered pumping turbine in 1953 [15].

Figure 1.8 A 10-megawatt wind energy installation at the Kaberten-Adrar site, 2014 [15].

Algeria has achieved limited progress in the development of renewable energy infrastructure, despite the implementation of a government program under the 2011-2030 action plan, which targeted to achieve a wind energy capacity of 5.1 GW [5]. Currently, the Ministry of Energy has already executed a single wind farm, with a capacity of 10 MW, located in the Kaberten area of Adrar city. The project Launched in 2014, is the first and only utility-scale wind energy facility at the national level. The production plant has 12 Gamesa wind turbines, each with a capacity of 850 kW, placed across a 30-hectare site (figure 1.8). The first stage aimed to provide as a foundational step toward the longer-term objective to construct 5 GW of wind power. However, the lack of further progress indicates substantial challenges for establishing renewable energy.

1.3.1.3 Geothermal energy potential

As indicated in figure 1.9, the integration of geological, geochemical, and geophysical data has permitted the production of a preliminary geothermal map, offering a foundational understanding of the country’s geothermal potential.

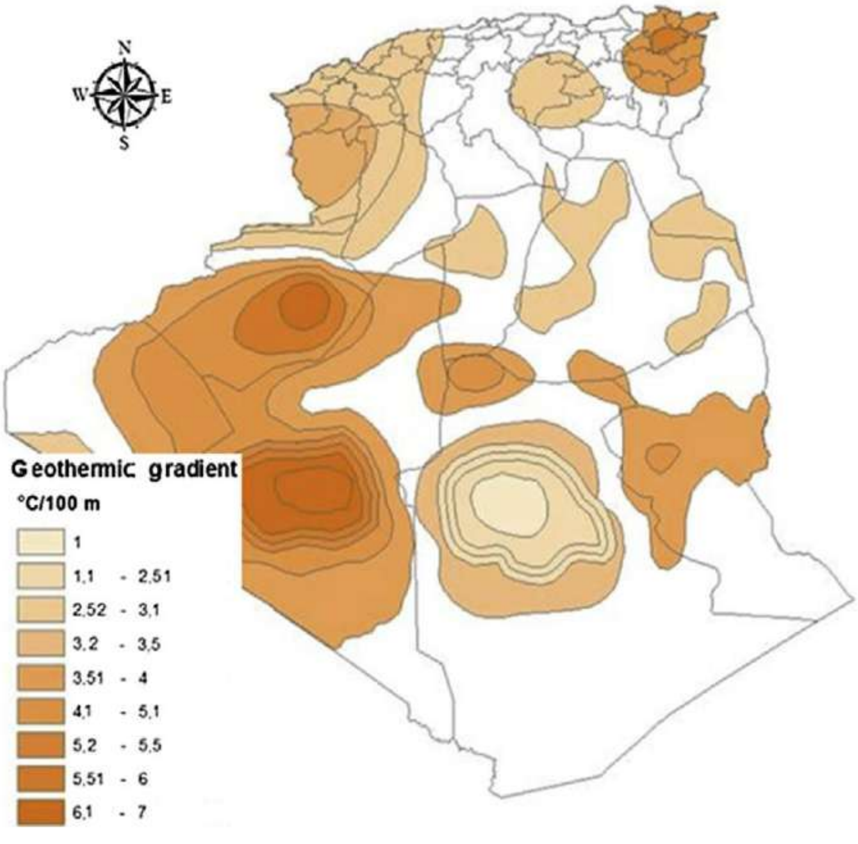

Figure 1.9 Geothermal gradient in Algeria [18].

In the northern regions, extensive surveys have documented over 200 hot springs, with about one-third (33%) indicating temperatures surpassing 45°C. The presence of these high-temperature springs shows wide-ranging geothermal activity, almost impacted by deep-seated geological formations and active fault structures. Such data analysis is crucial for analyzing the viability of geothermal energy consumption, as well as for future uses in direct-use heating, spa tourism, and other hydrothermal companies. Further detailed investigations, including subsurface temperature gradients and heat flow data, would be necessary to accurately assess the geothermal potential of these areas.

Biskra contains high-temperature geothermal resources, with recorded measurements of up to 118°C[18]. Thermal gradient studies indicate that in three distinct zones—Relizane and Mascara, Aïn Boucif and Sidi Aïssa, and Guelma and Jebel El Onk—the temperature rises by over 5°C for every 100 meters of depth.

1.3.1.4 Biomass potential

Algeria, a country with abundant renewable energy resources, has significant potential for biomass energy development. Despite its heavy reliance on fossil fuels, Algeria is increasingly exploring renewable energy sources, including biomass, to diversify its energy mix, reduce greenhouse gas emissions, and promote sustainable development [9]. Biomass energy, derived from organic materials such as agricultural residues, forest waste, and municipal solid waste, offers a sustainable alternative to fossil fuels.

Algeria possesses several sources of biomass, including agricultural residues from crops like wheat, barley, olives, and dates; forest residues from wood waste in the northern regions; animal waste from livestock farming; municipal solid waste from urban areas; and waste from the olive oil industry, such as pomace and wastewater [19]. These resources are abundant but remain underutilized, presenting a significant opportunity for energy production. However, biomass energy in Algeria is still in its early stages, with limited development and few projects. Some small-scale biogas plants have been established, primarily for rural electrification and waste management, and the Algerian government has introduced renewable energy targets, including biomass, as part of its National Renewable Energy and Energy Efficiency Program (2015–2030) [16].

Algeria can adopt various biomass conversion technologies to harness this potential. Anaerobic digestion can be used to produce biogas from animal waste and municipal solid waste, while combustion can generate heat and electricity from agricultural and forest residues [20]. Gasification offers the possibility of converting biomass into syngas for electricity or biofuel production, and bioethanol can be produced from sugar-rich crops like dates and olives. These technologies can help Algeria reduce greenhouse gas emissions, manage waste more effectively, and create economic opportunities, particularly in rural areas [21].

The environmental and economic benefits of biomass energy in Algeria are significant. By utilizing organic waste for energy production, the country can reduce landfill use and methane emissions, contributing to its climate commitments under the Paris Agreement [20]. Biomass projects can also create jobs and improve energy access in rural areas, promoting rural development. Additionally, biomass energy can help diversify Algeria's energy mix, reducing its dependence on fossil fuels and enhancing energy security [19]. Despite these benefits, several challenges hinder the development of biomass energy in Algeria.

One of the main challenges is the lack of awareness about the potential and benefits of biomass energy. Technological gaps, including insufficient infrastructure and expertise for biomass conversion, further limit progress [16]. High initial investment costs for biomass projects pose financial constraints, and inconsistent policies and a lack of incentives create regulatory barriers. Ensuring sustainable harvesting and utilization of biomass resources is another critical issue that needs to be addressed to avoid environmental degradation [21]. Despite these challenges, there are promising examples of biomass energy projects in Algeria. Small-scale biogas pilot projects in rural areas have demonstrated the potential for decentralized energy production. Initiatives focusing on converting olive oil waste into biogas and bioenergy have shown encouraging results, and efforts to convert urban organic waste into energy are being explored in major cities like Algiers and Oran. These case studies highlight the feasibility of biomass energy in Algeria and provide valuable lessons for scaling up future projects.

Algeria has significant opportunities to expand its biomass energy sector. Scaling up pilot projects to larger-scale installations, investing in advanced biomass conversion technologies, and fostering public-private partnerships are key steps for realizing this potential [16]. The government can play a crucial role by implementing favorable policies, incentives, and regulatory frameworks to promote biomass energy development. Collaboration with international organizations and the private sector can also help overcome financial and technological barriers [21].

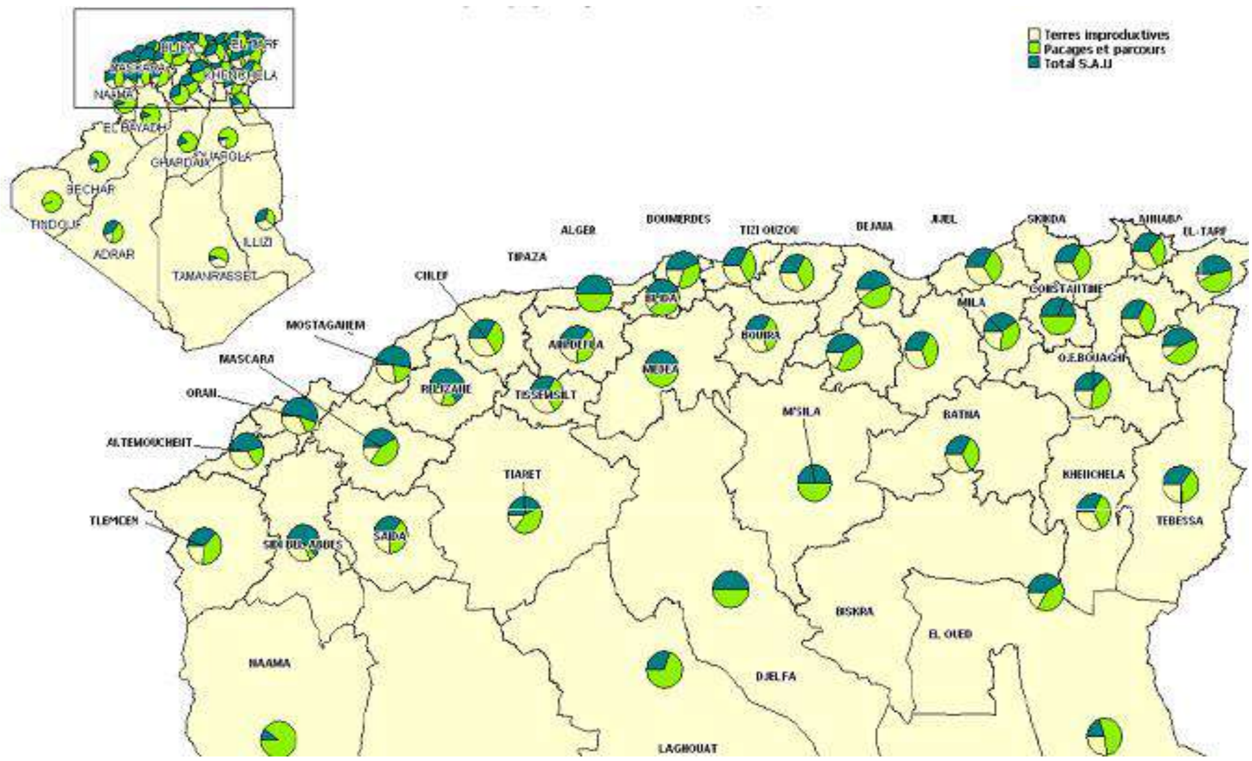

Figure 1.10 Distribution agriculture area [22].

Biomass energy holds significant potential for Algeria, offering a sustainable and renewable energy source that can contribute to energy security, environmental protection, and economic development. However, realizing this potential requires addressing technological, financial, and policy challenges. With the right strategies and investments, biomass energy can play a key role in Algeria's energy transition and help the country achieve its sustainable development goals. By leveraging its abundant biomass resources and adopting innovative technologies, Algeria can position itself as a leader in renewable energy in the region.

1.4 Algeria's energy consumption

Algeria's 2021 national energy balance indicates that overall energy consumption reached 67.2 Mtoe, reflecting a significant 1144.4% growth since 1976 (figure 1.11). Consumption is predominantly focused in three principal sectors: households and others, transportation, and non-energy industries. The household sector constitutes the predominant consumer, accounting for 46.7% of total consumption (about 23.43 Mtoe) – a growth mostly propelled by population increase. The transport industry experienced a notable increase, reaching 14.52 Mtoe in 2021, primarily attributed to heightened fuel demand from an expanding vehicle fleet, with over 270,000 new vehicles imported in 2015. Simultaneously, the non-energy industrial sector had consistent growth from 1.8 Mtoe in 1976 to 12.22 Mtoe in 2021, establishing itself as the third most energy-intensive sector following homes and transportation.

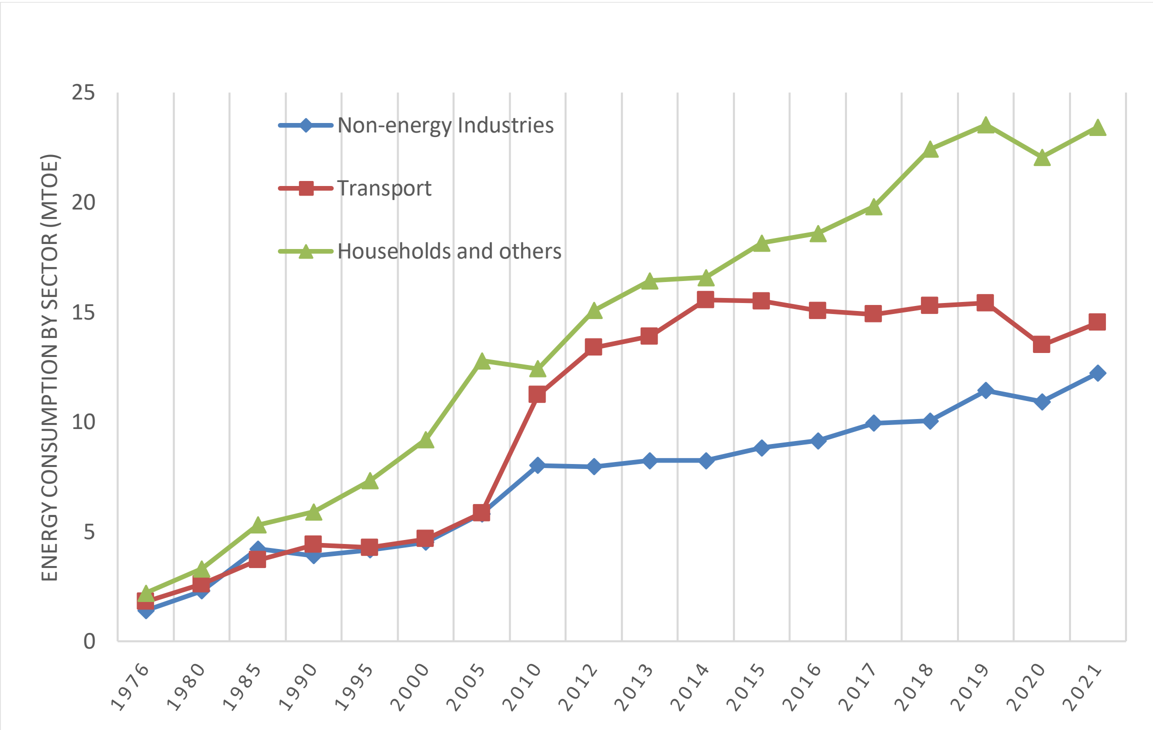

Figure 1.11 Energy consumption by sector from 1976 to 2021.

1.5 Energy Policy and Regulation in Algeria

The Algerian National Agency for the Development of Renewable Energy for the Promotion of Energy Efficiency was created in July 2011 [16]. It is responsible for the development of renewable energy in Algeria within the context of the national sustainable development and its linkages to the regional and possible international development strategies. In addition, the agency has been entrusted to manufacture passive and active solar and thermal equipment. Furthermore, it is responsible for promoting renewable energy technology development projects in cooperation with the industrial and financial sectors. The North African country seeks to diversify the use of its energy efficiency and to exhaustively incorporate renewable energy technologies in its electricity grid under the measures enshrined in the national program of Renewable Energy. The agency enjoys a high level of authority, as it has direct access to the Prime Minister via the Minister of Energy and Mines. In addition, this direct access avoids the avoidance of needless administrative bottlenecks to accord fast-track decisions on political and administrative lines.

The Ministry of Energy [9] offers guidance to other ministries in developing their energy policies when they impact the national energy policy. Through circular letters, the Ministry coordinates the activities and efforts of these organizations regarding energy issues involved. Energy challenges have implications across all economic sectors; thus, effective collaboration is crucial for a sustainable and comprehensive long-term energy policy. Recommendations regarding the measures for formulating the national energy policy have been centered on the institutions accountable for its development. It would guide the long-term planning process and create a comprehensive programming structure.

To have the capability to harmonize investments in the energy sector, the Algiers Convention established the Energy Council. Its objectives include advising Parties to the Convention on energy cartel control and security and the sustainability of the energy supply from production through processing, transportation, transiting, and distribution up to its final consumer. The Council invites the Parties to ensure full and transparent information on planned energy investments to allow coordination and avoid investment mismatches and vulnerability to undue energy domination.

1.5.1 Government policies on energy

The export of oil has historically been the pillar of Algerian economy on which its progress has been built. Algeria, like many other OPEC member countries, has seen its economy and development plans devastated due to the acute and rapid drop in prices of fossil fuels due to the COVID-19 pandemic [23]. Austerity measures are under consideration to provide the government with more time to evaluate its options in dealing with the fiscal pressure on the public treasury, which is likely leading to an important budget deficit. The economic plan is being implemented under the oversight of the International Monetary Fund. Consequently, it has been an increase in requests for the rationalization of governmental investment, the removal of excessive entitlement programs, and the exploration of alternatives to the predominant reliance on oil revenues as the only source of natural economic resources.

The rapid population growth and the continuous increase in the economy's absorptive capacity have resulted in an estimated doubling of energy demand between 2012 and 2021. An analysis of natural energy endowments in Algeria suggests that (i) being located in the most radiant location on earth, Algeria receives a solar energy resource that is about 25 times greater than world energy use, (ii) solar energy is now the least-cost option to generate electricity anywhere in the world, and (iii) solar energy consumption is predicted as the main future option to produce the energy needed by humanity and therefore control CO_2 emissions. A projection of energy demands up to 2030 suggests that demand growth will accelerate, and total energy consumption will add nearly 180 Mtoe reaching approximately 370 Mtoe by 2030 [9] [21]. On one hand, similar projections of electric energy demand suggest that demand will grow fivefold in the coming decades. On the other hand, it is estimated that with a current reserves per length of mine ratio of 0.0061, current coal resources are likely to last about 1645 years whereas the estimated life of Algerian oil resources is nearly 51 years, and the recent estimation indicates a possible extension of life for the current gas resources to 2075 with traditional exploration, and possibly beyond 2100 with an aggressive exploration strategy [23].

1.5.2 Regulatory framework for energy in economic sectors

The energy supply and demand of hydrocarbons and renewable energy resources at 2030 in the comprehensive high commission for hydrocarbon development and sustainable development scenario is measured. The total electric power demand will rise from 40.33 GW to 71.69 GW out of which 61.58 GW will be required from domestic fossil fuels, 1.41 GW from power plants and 8.7 GW from renewable energy resources in 2030. The capacity of hydrocarbon resources at 2030 under the assumptions made is computed. It is considered, on a conservative basis, that 60% of reserves estimates are recoverable at the most economic level. The developed model is a powerful tool to analyze the impact of the change of hydrocarbon production on domestic and world prices, on revenues and exports and imports of energy related commodities. A particular focus is devoted to the domestic market and price forecasts as well as the consumption of energy and petrochemicals up to 2030 as they relate to economic expansion and social development projects [23].

Table 1.1 presents the primary legislative and regulatory framework that governs Algeria's energy sector, highlighting a structured, state-centric system aimed at maintaining independent control over resources while responding to changing economic and strategic needs. The international energy outlook has undergone major changes recently. The perception of the role of oil and gas has evolved. Climate change concerns are likely to remain as a prime factor in comprehending the sustainability of primary energy demand and energy domestic and world prices levels over the next decades. Nevertheless, energy choices are not made on a level playing field.

Table 1.1 key legislative and regulatory texts for economic sectors

Thematic Area	Key Texts	Purpose & Focus
Core Hydrocarbon Law	Loi n° 05-07 (and its amendments: 06-10, 13-01)	The principal law governing all activities in the sector: exploration, production, transport, taxation, and contracts.
Upstream Activities	Décret n° 87-157, 87-158, 87-159, 88-34	Governs the upstream sector: classification of exploration zones, identification/control of foreign companies, conditions for granting/withdrawing mining titles.
Midstream: Transport & Infrastructure	Décret n° 88-35, Arrêté 1992, Décret 08-333, Décret 16-123	Regulates pipelines: their nature, safety procedures, pricing, and declarations of public utility for specific projects (e.g., Skikda to Constantine pipeline).
Taxation & Finance	Décret 06-440 (TPE), Finance Laws (14-10, 15-18, etc.)	Details specific taxes like the Exceptional Profits Tax (TPE) and annual finance laws that impact the sector's fiscal regime.
Environment, Safety & Conservation	Décret 94-43, Décret 05-476	Focuses on reservoir conservation, protection of water aquifers, and declaring specific areas (Hassi R'Mel) as major risk zones.
Downstream & Distribution	Décret 15-57	Sets conditions for the storage and distribution of petroleum products.
Energy Transition & Funds	Décret 15-319, Décret 16-121	Establishes and modifies the "National Fund for Energy Management, Renewables, and Cogeneration," showing a move towards sustainable energy.
International Cooperation	Décret Présidentiel 90-185 (Morocco), 06-102 (Peru)	Ratifies international agreements for energy cooperation and specific projects.
Recent Updates (2024)	Arrêté 2020 & its 2024 Annexes 1 & 2	Most recent activity: Precisely defining and updating the list of gas pipelines dedicated to the national market, indicating ongoing regulatory refinement.

The potential of saving carbon-intensive fuels by the development and deployment of wind, solar and nuclear power could reveal disruption of power plays in a world of shifty power positions. In addition, progress in energy technologies may widen the energy, economic and trade divides between countries. The impact will vary across countries and energy forms. Ultimately, the energy renaissance will likely shift more geopolitical power to oil and gas that are often associated with development and inflation issues [23].

1.6 Conclusion

The measurement and monitoring of the energy consumption of the activity are the first actions, which make it possible to reduce significantly the industrial energy consumption without heavy investment. Algeria as developing country has intensified its efforts to diversify its resources and ensure environmental sustainability by the implementation of energy and economic policies and strategies.

Chapter 02

Non-Energy Industrial Development in Algeria: Trends, Efficiency, and Environmental Implications

Chapter 02. Non-Energy Industrial Development in Algeria: Trends, Efficiency, and Environmental Implications

2.1 Introduction

Algeria, a resource-rich North African country, has long relied on hydrocarbons as the backbone of its economy. However, industrial diversification has become a central focus in recent years to ensure sustainable economic growth.

The industrial sector in Algeria has seen significant transformations throughout the decades, driven by state-led initiatives, foreign investments, and fluctuations in global economic trends. This chapter examines the historical development of Algerian industries, the key sectors that drive economic growth, the challenges they face, and their prospective potential.

2.2 Historical overview of Algeria's industries

Algeria's industrial history is characterized by substantial developments, influenced by both domestic policy and external factors. The Algeria's industrial sector has progressed from colonial era to post-independence policy, with varied levels of success and obstacles (Table 2.1). This overview will examine the historical evolution of Algeria's industry, emphasizing significant periods and sectors.

2.2.1 Pre-independence (Pre-1962): Colonial legacy

During French colonial rule (1830-1962), Algeria's economy was heavily oriented toward serving France's interests, with a focus on extracting raw materials while neglecting industrial development. The colonial administration prioritized the export of agricultural products, such as wine, wheat, and citrus fruits, and the extraction of minerals like iron ore and phosphates [24]. Industrial activities were minimal and largely limited to small-scale processing of raw materials for export, such as textiles and food processing [25]. This lack of industrialization left Algeria with an underdeveloped industrial base, which would later shape its post-independence economic policies [26]. The infrastructure development in Algeria was primarily aimed at facilitating the extraction and export of raw materials to France, rather than fostering broad-based industrial growth. The French colonial administration constructed railways, ports, and roads to connect resource-rich regions to export hubs. For instance, the railway network, which expanded significantly during the late 19th and early 20th centuries, was designed to transport minerals like iron ore and phosphates from inland mines to coastal ports such as Algiers, Oran, and Annaba. Similarly, ports were modernized to handle the export of agricultural products, including wine, wheat, and citrus fruits, which were cultivated on large-scale farms owned by French settlers [24]. However, this infrastructure was narrowly focused on serving colonial economic interests and did not support the development of a diversified industrial base. The railways and ports were primarily oriented toward export activities, with little investment in infrastructure that could facilitate domestic industrial development or regional trade. For example, industrial zones or manufacturing hubs were largely absent, and the infrastructure did not connect rural areas in a way that could stimulate local industries. Furthermore, the French colonial administration showed little interest in developing energy infrastructure, such as electricity grids, which are critical for industrial growth [27].

As a result, while the infrastructure built during the colonial period enabled the efficient extraction and export of raw materials, it failed to lay the foundation for a self-sustaining industrial economy. This legacy of uneven and export-oriented infrastructure development would pose significant challenges for Algeria's post-independence industrialization efforts.

2.2.2 Post-independence Era (1962-1990): Socialist industrialization

After 1962, Algeria adopted a socialist economic model, emphasizing state control over key industries through the nationalization of foreign-owned assets, including oil and gas resources, and the establishment of state-owned enterprises (SOEs). Key policies included the 1966 nationalization of mines, which brought iron ore and phosphate operations under state control, and the 1971 nationalization of hydrocarbons, which led to the creation of Sonatrach, the national oil company [28]. The government prioritized heavy industries such as steel, petrochemicals, and cement to reduce import dependence and build a self-reliant economy, resulting in the establishment of major industrial complexes like the ArcelorMittal steel plant in El Hadjar and the Skikda petrochemical complex [25]. While these efforts achieved significant growth in the hydrocarbon sector, which became the backbone of the economy, challenges emerged, including inefficiencies in SOEs due to bureaucratic management and a lack of competition, as well as over-reliance on hydrocarbons, which made the economy vulnerable to global oil price fluctuations [27,29].

2.2.3 Economic liberalization and reform (1990-2000): Transition to a market economy

In the late 1980s, Algeria faced an economic crisis triggered by falling oil prices, high debt, and inefficiencies in its state-led economic model, prompting the government to adopt market-oriented reforms in the 1990s. Key reforms included the privatization of state-owned enterprises to encourage private sector participation, the reduction of trade barriers to promote exports, and the introduction of laws to attract foreign direct investment (FDI), particularly in the hydrocarbon sector [29]. These reforms had mixed impacts on industries: the hydrocarbons sector remained dominant, with increased foreign participation in exploration and production, while the manufacturing sector struggled due to competition from imports and a lack of competitiveness [28]. However, the reforms also spurred the emergence of small and medium-sized enterprises (SMEs), which began to play a more significant role in sectors such as textiles, Food produxts, and construction, marking a shift toward a more diversified economy [25,27].

2.2.4 Contemporary industrial landscape (2000-Present): Diversification and modernization

Since 2000, Algeria has continued to invest heavily in its hydrocarbon sector, with Sonatrach leading efforts to modernize infrastructure and explore new reserves. Key developments include the expansion of liquefied natural gas (LNG) production and export facilities, as well as the development of new oil and gas fields, such as Hassi Messaoud and In Salah, which have strengthened Algeria's position as a major energy exporter [2]. Despite these advancements, the sector remains heavily reliant on foreign technology and investment, highlighting the need for further modernization and innovation [28].

Recognizing the risks of over-reliance on hydrocarbons, the Algerian government has launched several initiatives to diversify the economy. The National Industrial Development Plan (2016-2030) is a comprehensive strategy aimed at promoting non-energy industries, including manufacturing, renewable energy, and information and communication technology (ICT) [5,16]. Additionally, Algeria has prioritized renewable energy through the Renewable Energy and Energy Efficiency Program, which aims to generate 22 GW of electricity from renewable sources, particularly solar power, by 2030 [16]. These efforts reflect a growing commitment to sustainable economic development.

To attract investment and promote value-added industries, the government has established industrial zones and parks. Key projects include the Bellara Steel Complex, a joint venture with Qatar Steel designed to produce steel for domestic and export markets, and the growth of the pharmaceutical and automotive industries through partnerships with foreign companies [22]. These initiatives have helped create jobs and reduce reliance on imports, though challenges such as bureaucratic inefficiencies and infrastructure deficits persist.

Algeria's industrial landscape faces several challenges, including persistent reliance on hydrocarbons, infrastructure deficits, bureaucratic hurdles, and a need for technological innovation and skilled labor [30]. However, opportunities abound, particularly in renewable energy, where Algeria's vast solar potential remains largely untapped. Additionally, growing regional and international partnerships offer avenues for knowledge transfer and investment, which could drive further industrial growth and diversification [31].

Table 2.1 Phases of Industrial Development in Algeria

Period	Key Focus & Policies	Key Outcomes & Challenges
Pre-Independence (Pre-1962)	Economy oriented to serve France; focus on extraction of raw materials; infrastructure built for export.	Underdeveloped industrial base; export-oriented infrastructure (railways, ports). Challenges: Neglected industrial development; no foundation for a diversified, self-sustaining economy.
Post-Independence Era (1962-1990)	Socialist model; state control and nationalization (mines, hydrocarbons); emphasis on heavy industry and self-reliance.	Significant growth in hydrocarbons; established heavy industrial base. Challenges: Inefficient state-owned enterprises (SOEs); over-reliance on hydrocarbons; vulnerability to oil prices.
Economic Liberalization and Reform (1990-2000)	Market-oriented reforms; privatization of SOEs; reduction of trade barriers; laws to attract Foreign Direct Investment (FDI)	Spurred growth of SMEs; shift towards a more diversified economy. Challenges: Manufacturing sector lacked competitiveness; hydrocarbon dominance persisted.
Contemporary Landscape (2000-Present)	Continued investment in hydrocarbons; initiatives for economic diversification (National Industrial Development Plan 2016-2030); promotion of renewable energy and value-added industries.	Strengthened energy exporter position; job creation in new sectors; reduced import reliance in some areas. Challenges: Persistent reliance on hydrocarbons; bureaucratic inefficiencies; infrastructure deficits; need for skilled labor and technology.

2.3 Algeria's industrial structure

One of the most important sectors of the Algerian economy is the oil industry, which, despite being less important now than before independence, continues to dominate [9]. Still, with the growth of the population – from 4 million in 1900 to around 40 million in 2010 – food dependence increased, resulting in a financing program to support local production was launched. On the one hand, the strong growth of population favored and amplified Algeria food dependence, which pushed the Algerian government to launch a program to sustain this agriculture, support farm producers, reduce the dependence on imports [22]. Moreover, this sector was neglected until recently by the Algerian government, instead giving preferences to

Algerian heavy industries. Thus, with very few exceptions, the sugar and dairy markets were not covered by the national production. This situation drove the government to take charge of the markets and quickly obtained an agreement with major importers to supply these commodities locally. Then, the Algerian government launched a general program for local production and to build local industries for sugar and milk products. The Food Products and Beverages industry was identified as a topic by the Algerian authorities, but many other topics remained neglected. It was ensured that a weighting on industry means less scrutiny of finished goods, as processing probably remains less important in the local economy. In other words, the Algerian industry does not seem prepared for the competition: indeed, the country's large population is far from the wealthier nations, both in purchasing power parity and in nominal terms. Products of engineered goods are particularly viewed upon as unreliable or costly, which explains the non-negligible smuggling activity.

Algeria has a varied industrial structure; however, it is predominantly dominated by the hydrocarbons sector. The country's industrial sector is primarily categorized into energy and non-energy industries, reflecting of its economic structure and distribution of resources.

2.3.1 Energy industries

The energy industry in Algeria plays a crucial role in the country's economy, encompassing both fossil fuel and renewable energy sectors. These industries focus on the production, processing, and distribution of energy resources, contributing significantly to government revenue and national exports [22].

2.3.1.1 Oil and Natural Gas industry

The oil reserves of Algeria are estimated at over 12 billion barrels and gas reserves are enough for over 150 years of producer consumption at the current rate of exploitation [1]. A significant share of non-conventional hydrocarbons, allowing assessment of shale gas production, is believed to be available in Algeria's geographic domain. Algeria is notable as an ancient oil and gas-producing region in the world.

Algeria's oil and natural gas sector is the backbone of its economy, with extensive activities in exploration, extraction, refining, and export. The industry is dominated by Sonatrach, the state-owned company, which controls most of the country's hydrocarbons production and infrastructure. Several foreign companies, including BP, Total, and Eni, participate in joint ventures to enhance resource extraction and technology transfer [3].

The sector produces a variety of output products, including crude oil, natural gas (both piped and liquefied natural gas - LNG), and refined petroleum products such as gasoline and diesel. Algeria possesses an extensive energy infrastructure, with major pipelines, LNG plants, and export terminals located in key sites like Skikda and Arzew [23].

From an economic perspective, the hydrocarbons industry is the most significant contributor to the national economy, accounting for approximately 20% of GDP, 95% of export earnings, and 60% of government revenue [2]. However, despite its dominance, the sector faces challenges such as fluctuating global oil prices and the need for economic diversification.

2.3.1.2 Power generation (Electricity production)

The electricity generation sector plays a crucial role in Algeria's energy industry and includes both fossil fuel-based power plants and renewable energy power plants.

Fossil Fuel-Based Power Plants: Most Algeria's electricity is generated from gas-fired thermal power plants, given the country's vast natural gas reserves. Additionally, combined-cycle power plants, which improve efficiency by using both gas and steam turbines, are widely utilized [9].

Renewable Energy Power Plants: Algeria is developing solar, wind, and hydroelectric power plants to diversify its energy mix. Notable projects include the Hassi R'Mel hybrid power plant, which integrates solar energy with natural gas, and several large-scale solar farms [20].

2.3.1.3 Renewable energy industry

In recent years, Algeria has taken steps to diversify its energy mix by investing in renewable energy sources such as solar, wind, and hydropower. The government has launched several key initiatives to develop the sector, most notably the Renewable Energy and Energy Efficiency Program, which aims to produce 22000 MW of renewable energy by 2030 [5].

Among the most prominent solar energy projects is the Hassi R'Mel hybrid power plant, which combines solar and natural gas to improve efficiency. Additionally, several large-scale solar farms have been developed to harness the country's vast solar potential [20]. The output products of these initiatives include electricity generated from solar, wind, and hydropower, which contribute to the national grid and reduce dependence on fossil fuels.

Although still an emerging sector, renewable energy holds significant economic potential for Algeria. It not only provides a sustainable alternative to hydrocarbons but also aligns with global energy transition trends. Expanding investment in renewables could strengthen energy security, create jobs, and support long-term economic growth [20].

2.3.2 Non-energy Industries

Non-energy industries in Algeria encompass a diverse range of sectors whose output is not directly related to energy production. These industries play a crucial role in economic diversification, employment generation, and industrial development.

Non-energy industries in Algeria experienced several boom periods, punctuated by strong growth in value added in the 1970s, subsequently receding but still remaining positive until 1987. Real value added trend growth of Non-energy sector was slightly negative in preparation for the appetites of the early and mid-1990s. They finally reacted positively to the incentives and promotions created for them [9]. Despite the impacts of the global recession in the late 1990s, the growth in non-energy sector continued. Apart from processes, products, and services widely acknowledged as the basic inputs for von-energy sector, quality levels, data, and knowledge made available by the underlying technologies developed accordingly largely contributed to non-energy sector and value added growth worldwide. Supporting the long-run performance of mining, quarrying, construction, agricultural, and light industries other sectors providing inputs at prices and quality levels matched or better than imported ones would be subcritical to overall growth [22]. Investment figures were successfully complemented so that the overall price index was utilized to convert nominal values to real ones. Mining, quarrying, natural gas, crude oil extraction, and basic manufacturing were the only sectors in which portfolio veil adjustments were possible. Even then considerable caution should be exercised in interpreting the sectoral performance of each.

2.3.2.1 Construction Materials Industry

The construction materials industry in Algeria is a vital component of the manufacturing sector, encompassing the production of cement, bricks, ceramics, and other building materials. Algeria is one of the largest cement producers in Africa, with an annual production capacity exceeding 30 million tons [32]. This industry supports the construction and public works sector, which contributes 10% to GDP [22]. However, it faces challenges such as high energy consumption, reliance on imported equipment, and environmental concerns related to emissions and resource extraction. Despite these challenges, the industry has significant growth potential due to increasing demand for housing and infrastructure projects, as well as opportunities for exporting construction materials to neighboring countries.

2.3.2.2 Iron and Steel, Mechanical, Electronic, and Electric Equipment Industry

The iron and steel, mechanical, electronic, and electric equipment industry is a cornerstone of Algeria's industrial sector. The Bellara steel plant, a joint venture with QatariSteel–AQS, produces over 1.9 million tons of steel annually [22], supporting downstream industries such as construction and automotive. This sector contributes to job creation and technological development but faces challenges like high production costs, reliance on imported raw materials, and limited global competitiveness. Growth prospects include expanding steel production, developing downstream industries, and forming partnerships with foreign companies to enhance technology transfer and innovation.

2.3.2.3 Chemistry Industry

Algeria's chemistry industry includes petrochemicals, fertilizers, plastics, and pharmaceuticals. The Skikda and Arzew petrochemical complexes are central to this sector, producing fertilizers, plastics, and other derivatives. Petrochemicals account for a significant share of non-oil exports, while the pharmaceutical sector meets 40% of domestic demand [22]. Challenges include high energy and water consumption, limited value-added production, and reliance on imported raw materials. Growth opportunities lie in expanding petrochemical production, diversifying into specialty chemicals, and fostering partnerships with foreign firms to boost the pharmaceutical sector.

2.3.2.4 Food Products, Beverages, and Tobacco Industry

The "food products, beverages, and tobacco industry" is a key player in Algeria's non-energy sector, encompassing the processing of agricultural products, beverages, and tobacco. This industry contributes 5% to GDP and employs a large workforce, particularly in rural areas [22]. It also helps reduce reliance on food imports, which account for 20% of total imports. However, the sector faces challenges such as limited access to modern technology, packaging materials, and competition from imported products. Growth prospects include expanding processed food exports to regional markets and investing in modern processing facilities and technology to enhance competitiveness.

2.3.2.5 Textile, Clothing, and Leather Industry

The textile, clothing, and leather industry, though historically significant, has declined due to competition from imports and a lack of modernization. It contributes less than 1% to GDP but remains important for employment, particularly in rural areas [22]. Challenges include outdated machinery, lack of investment, and competition from low-cost imports, particularly from Asia. However, the industry has potential for revival through modernization, niche markets (e.g., traditional clothing and handicrafts), and export opportunities to African and European markets.

2.3.2.6 Construction and Public Works Industry

For the construction sector, the year 1962 is regarded as one of the most important turning points because the construction activity in Algeria was put on a new footing [22]. This period after independence in 1962 was marked by the formation of numerous national companies, the founding of several public and semi-public organizations to assist in the building sector, and the establishment of training centers for construction engineers and workers. The main construction activities that were the responsibility of state-owned companies involved construction of waterworks, electricity generation facilities and networks, communication facilities and a few highways construction works. There was also an era of great planning during this period where in 1976 the government established the Algerian Department of Transportation Engineering. According to the national will, plans were made to establish industry supervisory companies to promote the development of major transportation sectors such as highways, maritime transport, air, and rail. The Department of Transportation was established in 1955 and ordered the establishment of transportation command companies in 1963 and 1965 to manage the Algerian railways and maritime transport, respectively. To provide design drawings based on metal structures and standard components for future transportation trunk lines, a company was established in 1985. Another company was established in 1984 and operates independently, responsible for participating in the design and construction of transportation facilities. Algeria's infrastructure is relatively underdeveloped, with a low stock of fixed assets and a limited number of important transportation infrastructure, lagging behind in development, with 35 newly built counties among 28 provinces and 580 counties, totaling 1093 counties under construction. Due to the lack of large-scale construction projects with complex construction conditions and poor geological conditions, the Algerian construction industry has been unable to form a more reasonable industrial structure. Foreign construction companies still dominate the Algerian construction market, and there are no constraints on their investment in self-owned funds, advanced technology and equipment, special processes, and skilled technical workers. Therefore, the government continuously reorganizes the construction industry strategy, adjusts the industrial structure, and promotes faster and better development of the construction industry.

The “construction and public works” industry is a major driver of Algeria’s economy, involving the construction of residential, commercial, and public infrastructure. Major projects include the East-West Highway, Algiers Metro, and large-scale housing programs. The sector contributes 10% to GDP and employs a significant portion of the workforce [22]. However, it faces challenges such as bureaucratic delays, corruption, and reliance on imported construction materials and equipment. Growth prospects include continued investment in infrastructure and housing projects, as well as the potential for public-private partnerships to improve efficiency and project delivery.

2.3.2.7 Other Industries

The "other industries" category includes smaller sectors such as paper, wood, and handicrafts. While these industries contribute modestly to GDP, they play an important role in local economies and job creation, particularly in rural areas. Challenges include limited access to modern technology, markets, and competition from imported goods. Growth opportunities lie in developing niche markets, enhancing export potential, and investing in modernization and marketing to increase competitiveness.

2.4 Energy consumption of non-energy industry

Figure 2.1 presents a detailed view of the percentage contributions of different industrial sub-sectors to Algeria's total industrial energy consumption from 2002 to 2021. A significant trend has been observed in the construction and public works sector, which shows a steady increase over the two decades. Starting with a modest contribution in the early 2000s, its share rises gradually, particularly after 2010, reflecting the growing role of construction activities in the country’s economic development. In contrast, sub-sectors such as textiles, clothing, leather, food products, beverages, and tobacco exhibit relatively stable and modest shares, indicating that their energy consumption has not drastically shifted over time.

The results also show a significant decrease in the share of the iron and steel, mechanical, electronic, and electrical equipment industries. This decreasing tendency shows that industrial priorities may evolve, possibly as a result of improved energy efficiency or changes in manufacturing methods within certain sectors. Furthermore, while the chemical sub-sector is growing, it is more obvious in later years, indicating changing industrial practices or market demands.

The examination of the data presented in figure 2.1 demonstrates changing patterns in Algeria's industrial energy usage. With "Other Industries" constantly being the greatest energy consumer, shifts in construction and public works, as well as a diminishing share of key manufacturing sectors, reveal a dynamic economic environment that has experienced significant transformation over time.

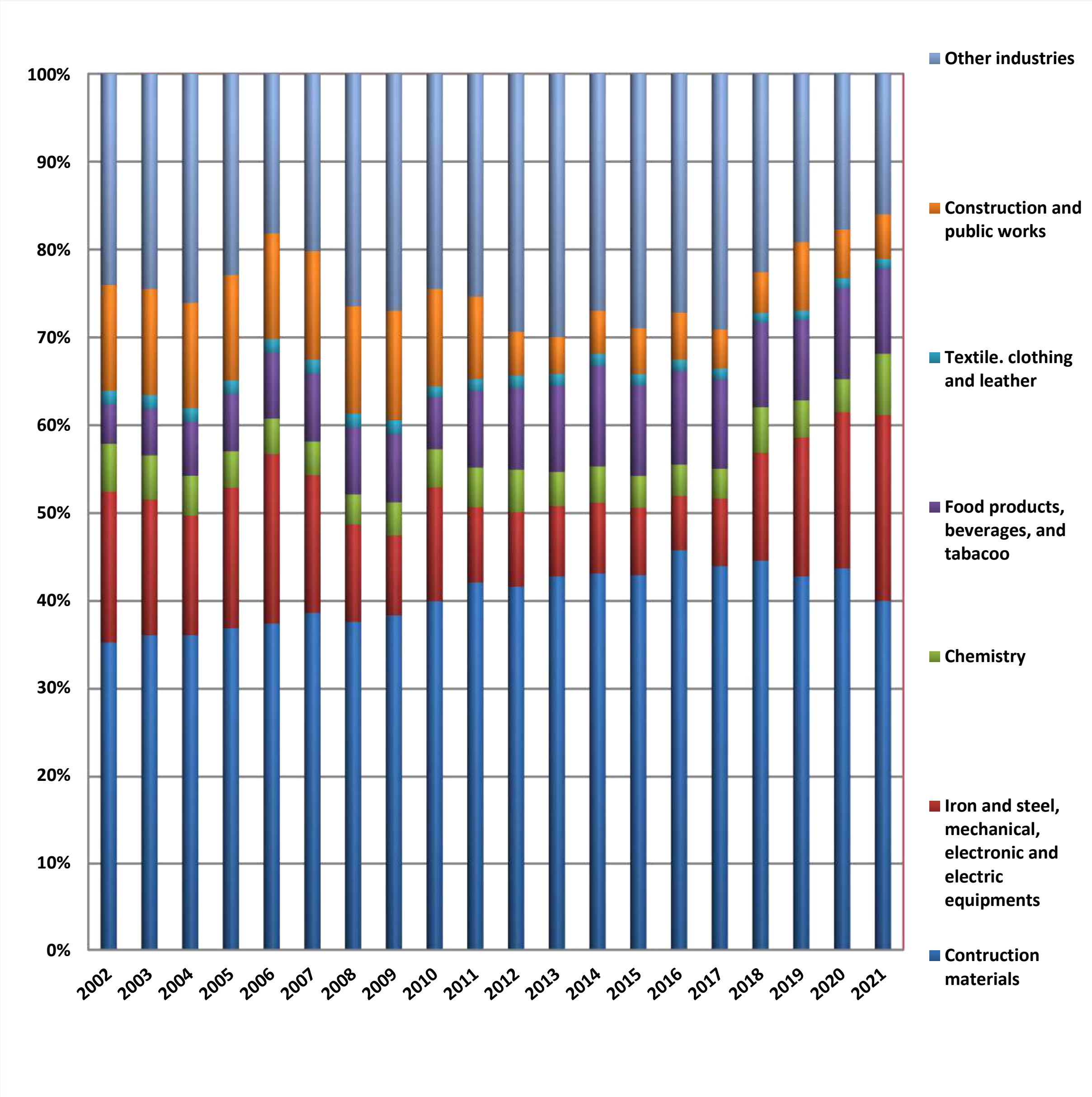

Figure 2.1 Industrial energy consumption by sub-sector in Algeria (2002-2021).

2.5 Value added of non-energy industry

Figure 2.2 presents the value added by various industrial sub-sectors in Algeria from 2002 to 2021, reflecting the contribution of different industries to the country's economic growth and industrial development. The data highlights fluctuations in industrial performance, indicating periods of expansion, stagnation, and contraction across various sectors.

The “construction materials” and the “iron and steel, mechanical, electronic, and electric equipment” industries show significant variations over time. These fluctuations may be linked to infrastructure projects, investment cycles, and demand for raw materials in construction and manufacturing. The peaks in value added suggest periods of economic expansion, while the declines could indicate reduced public spending, market downturns, or supply chain disruptions.

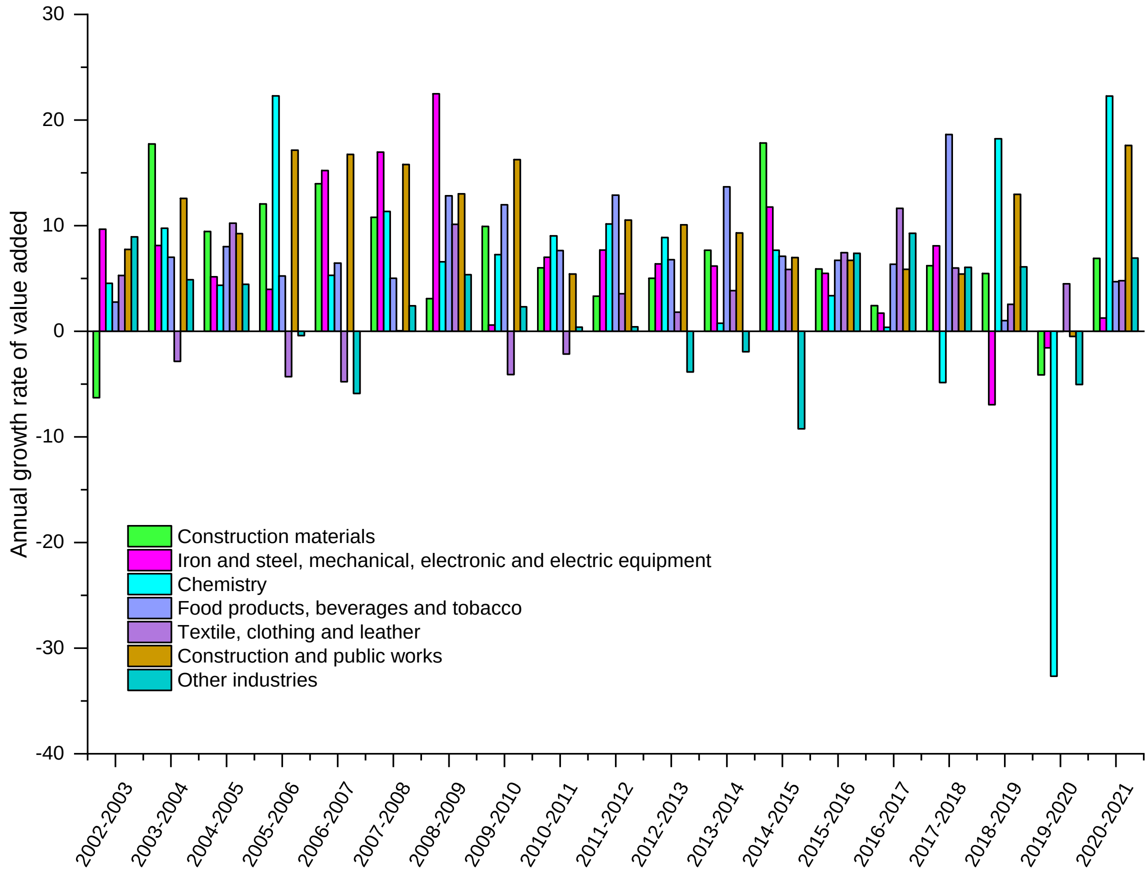

Figure 2.2 Annual growth rate of sub-sectoral non-energy industrial value added from 2002 to 2021.

The “chemistry” and “food products, beverages, and tobacco” industries exhibit a relatively stable yet growing trend, suggesting consistent demand and steady industrial expansion. The “textile, clothing, and leather” industry appears to have a lower value-added contribution, likely due to limited industrial competitiveness, import dependency, or structural challenges within this sector.

One of the most noticeable trends in the figure is the sharp negative fluctuations in the “construction and public works” and “other industries” in specific years. These sharp declines may be linked to economic recessions, regulatory changes, or reduced investment in large-scale infrastructure projects. The variability in these sectors indicates their sensitivity to external economic factors, government policies, and market dynamics.

2.6 Energy intensity of non-energy industry

Figure 2.3 illustrates the industrial energy intensity across various sub-sectors in Algeria from 2002 to 2021, highlighting trends in energy efficiency and consumption patterns within the country's industrial landscape. Energy intensity, defined as the amount of energy consumed per unit of economic output, is a crucial indicator of industrial efficiency and sustainability.

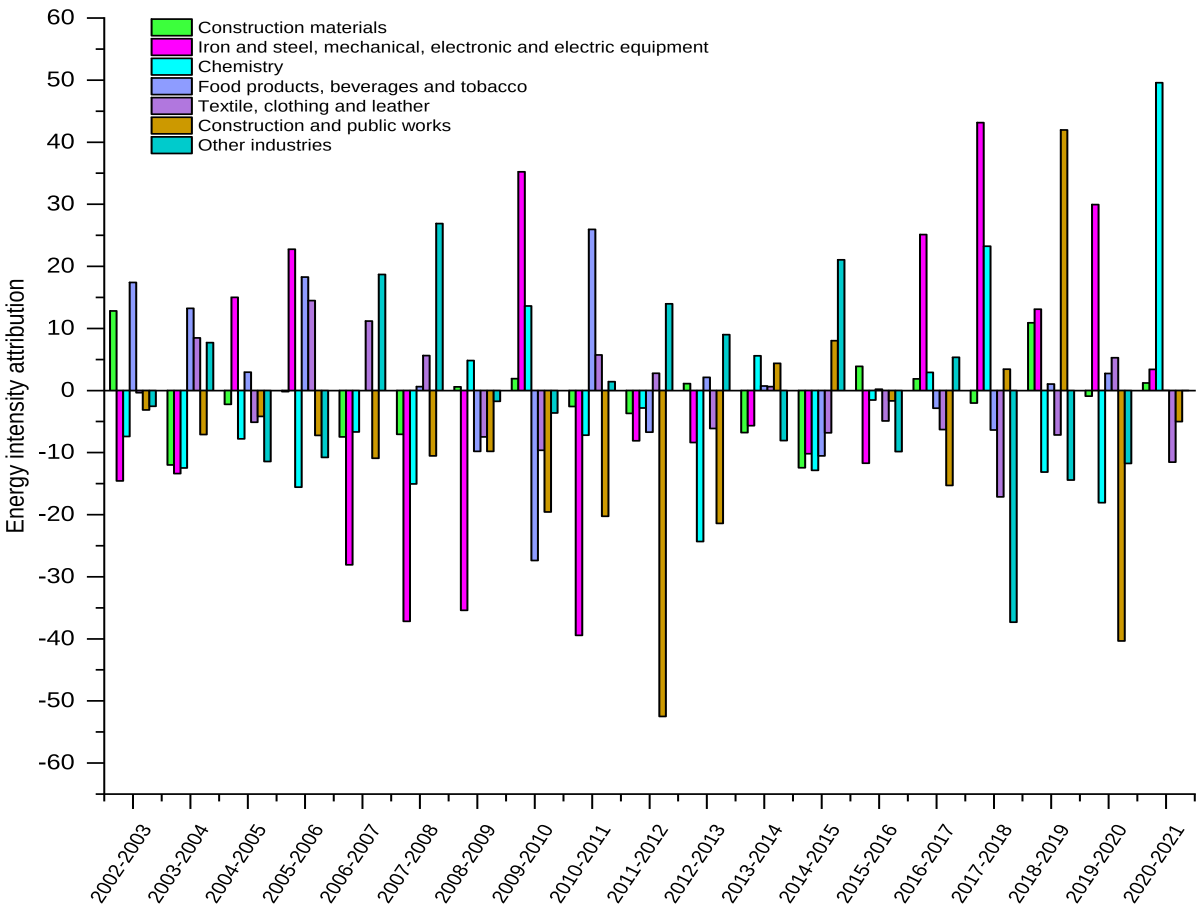

Figure 2.3 Energy intensity attributed by non-energy industry subsector from 2002 to 2021[10].

A key observation from the figure is the fluctuating energy intensity across different sub-sectors, reflecting varying degrees of energy efficiency improvements, technological advancements, and industrial expansion. The “iron and steel, mechanical, electronic, and electric equipment” and the “chemistry” exhibit notable variability in energy intensity, suggesting changes in production processes, energy-saving initiatives, or shifts in industrial activity. The “construction materials” industry shows similar fluctuations, which could be linked to periods of increased construction activity requiring intensive energy use, followed by efficiency gains or slowdowns in infrastructure projects.

The “construction and public works” and the “other industries” industries demonstrate significant declines in certain years, indicating potential periods of reduced industrial output or the implementation of energy-efficient technologies. Sharp negative values in these sectors may suggest economic downturns, policy interventions, or structural changes that led to lower energy consumption relative to output. In contrast, the “food products, beverages, and tobacco” and the “textile, clothing, and leather” industries display relatively stable energy intensity levels, implying a consistent balance between production growth and energy consumption.

2.7 Technological advancements and innovation in non-energy industry

Over the decades, advances in technology have dramatically transformed many of the industries involved in the production of goods and services. The non-energy industry in developing countries is undergoing a transformative phase driven by the adoption of cutting-edge technologies. These advancements are not only enhancing efficiency and productivity but also enabling these countries to compete on a global scale.

Innovation in industrial processes has emerged as a critical driver of economic growth, particularly in developing regions. By integrating advanced technologies, fostering research and development, and promoting sustainable practices, manufacturing innovation can unlock significant economic potential. In “Food products, beverages and tobacco” industry, the solar drying process proposed by farmers in the south of Algeria provides a post-harvest treatment with no cost due to its successors. This treatment has led to the high quality of Algerian Deglet-Nour dates have been produced and exported [33]. In the north, Algerian farmers have also managed the transport of grapes and introduced a dehydration process in factories; this method is not yet suitable for the south but will be essential in the future. Producing raisins from areas producing both varieties of grapes will be an investment opportunity for Algeria.

As contiguous areas of selected grape varieties, it will provide quality grapes for dehydration without transport cost. In recent years, due to Algeria being at the mercy of water scarcity, a need to manage the water demand became crucial [22]. Since 2006, or even earlier, Water Saving Technologies (WST) were promoted to make better use of the available water in agriculture. It can be achieved by using less water to irrigate, putting it in irrigation systems that apply water more efficiently, or by changing agricultural practices that make better use of the water supplied. Like implemented worldwide, usually pressurized irrigation systems were introduced in Algeria, particularly sprinkling, and dripping. It has been shown that this increase in irrigation investment enhances crop water allocation and inefficient management has not affected quantity of water consumed statistically positively but affected yield and water productivity positively. In the opportunistic approach, working properly it is the key to increase rapidly the productivity of crops, areas and/or farmers globally.

In the implementation of a more preventative approach that can be practiced in Algeria is the proper management of the water and another input used to crop production. Today, the agriculture sector needs to adapt to irrigation problems whether they are regular due to climatic or institutional shocks. In the absence of adequate infrastructure to provide fully planned WST, new technologies and means using smart agriculture which have been developed rapidly lately to reduce loss and enhance productivity of water used shall provide an opportunity for developing countries and Algeria in particular. These technologies offered by intelligent agriculture can be a crucial tool for boosting the development of Algerian agriculture and meeting the needs of a rapidly growing population.

Smart agriculture and its various applications used in city and urban, farmland and pasture, forestry and fishery can ensure better quality of numerous different kinds of food production. Smart agriculture is the key strategy to achieve food security and the emergence of ecological agriculture provides healthy products of good nutritional quality. Being a developing country situated in the heart of the Mediterranean, as an agricultural producing country Algeria has many agricultural opportunities. Unfortunately, innovative technologies acquisition in the agriculture sector is at a very poor level, below five undergoing either tests or validation.

However, the relative importance of adopting new technology in agriculture sectors is more critically important compared to that in other sectors. Being unable to adopt new technologies, it has to be understood that productivity in this sector will remain low and be the origin of a growing social crisis and of food security too. Farmers still prefer by preference question more traditional methods and technologies and soil management the relative importance of adopting new technology in the agriculture sector is troops unable to adopt new technologies, it has to be understood that productivity in this sector will remain low. However, it cannot be imposed, farmers of older generations must see a lot of education, we do not have younger farmers willing to follow educational programs and conventional techniques seem to be accepted even bakery waste or aromatic herbs. Focus on education might not expect a quick return on investment. Smart agriculture can reduce field variation and differences in practices can now be monitored through adopting new technologies in agriculture. The whole society diagnosed by mental hardships that hinder change. In recent years, the post-harvest scenario in Algeria is not yet fully developed. The storage process is being devised so that it works efficiently, and the packaging process is still mostly simple. Farmers are using innovative technologies and methods not only to improve productivity and reduce post-harvest losses but also this approach will allow farmers to adapt to climate change, manage inputs better, increase their yields and improve the quality of their crops.

2.8 Sustainability and environmental considerations

Most global markets are opening to emerging competition, while existing domestic markets are getting more competitive. The innovation has emerged as a significant competitive advantage and an important driver to sustain and enhance productivity, having a large ripple effect on larger clusters of product value [22] [34-35]. Despite the positive effects of Foreign Direct Investment (FDI) in whether in developed and developing countries, foreign companies still prefer developing countries to invest. That’s why to attract more foreign investments, Algeria should provide not only market opportunities but also favorable business environment and ensure sustainability [36]. Different measures can be taken to improve the investment climate. Environmental strategies are of prime importance among those. In the wake of economic growth and industrialization, pollution can threaten a country’s economic growth and quality of life. To avoid technical obsolescence and to lessen the pressure on the environment, it becomes necessary to implement clean practices. In this study, the indirect link between the development stage and environmental pressure is examined according to FDI and electricity usage in Algeria. Significant pollution control measures should be taken to avoid the deterioration of Algeria’s environment. For this aim, economic activities and foreign investment inflow that have been attracting more attention should be directed towards high-tech and clean ones. This crucial point directly involves strict environmental regulations to control corner cutting investment practices and to protect local people from the negative effects of production activities.

Developing good long-term environmental strategies for better economic growth and more FDI is an innovative idea. A clean energy source is vital as the present energy use in Algeria, which was almost fossil based, mainly determined environmental pressure. To comply with international norms, it becomes compulsory for a country to control the use of products that have a negative effect on the environment, although innovative and green technologies should ease the adherence to those rules. Basic strategies to cope with future sustainable growth consist of three main parts, among which government interventions are essential. The Administration should improve clean energy sources. The private sector should implement measures to attract business to the country. As a determining fact on compliance with those norms, investment operations should generally be controlled.

2.9 Impact of Industrial Growth on Environment

Algeria stands out as a major country possessing several abundant natural resources, notably oil and natural gas [2]. However, contrary to expectations given its geographic size, rich mineral resources, and favorable climate for agriculture, the development of the industrial sector in Algeria has not met expectations. Employing a nonlinear dynamic approach, the empirical evidence confirms that an N-shaped environmental Kuznets curve connection between economic growth and the ecological footprint holds during the previous era [36]. The transition from a developing to a grown stage occurs, where foreign direct investment and electricity consumption exert direct effects on the ecological footprint (EFP). The econometric results confirm an interaction between foreign direct investment and electricity consumption that indirectly connects with the ecological footprint, meaning that modern techniques should be employed to avoid technical obsolescence and reduce environmental pressure.

Empirical evidence supports the pollution haven hypothesis, confirming a direct connection between foreign direct investment and the EFP. This direct linkage implies the necessity of implementing a high-tech industry in Algeria to reduce the pernicious effects of foreign direct investment on the environment. The electricity consumption directly correlates with the EFP, suggesting that fossil sources dominate the energy mix in Algeria. The Government has different political systems, economic development stages, and energy consumption types, meaning they implement different energy policies [37]. In Algeria, although the oil and gas sector, is an engine for socioeconomic development, the low diversification of the economy makes the country fragile to oil shocks. Therefore, investments in clean industries, together with the enforcement of stringent environmental regulation, would diminish the ecological pressure.

The econometric procedure builds a framework modelling product innovation based on a nonlinear dynamic perspective through a systemic approach [38]. The study showed that both government and private industry should coordinate active measures to tackle complex climate change problems. The Government should promote clean-energy sources in order to increment the renewable sources share in the energy mix, to reduce ecological footprints in a context where fossil-fuel energy dominates. The private sector should implement clear measures in strategic sectors like tourism or the high-tech industry, to fight against the petrify path of technical progress.

2.10 Conclusion

Algeria's non-energy industries are critical for economic diversification, job creation, and reducing reliance on hydrocarbons. While sectors like "construction materials", "iron and steel", and "Food products, beverages and tobacco" show significant potential, challenges such as high energy consumption, reliance on imports, and limited competitiveness must be addressed. Strategic investments, partnerships, and policy reforms can unlock the growth potential of these industries, contributing to a more resilient and diversified economy.

Chapter 03

Energy Consumption in Algeria’s Non-Energy Industrial Sectors: An Analysis of Key Drivers

3.1 Introduction

Energy consumption in non-energy industrial sectors is an important indicator in Algeria's economic and environmental context. In the context of economic diversification and reduced dependence on hydrocarbons, it is crucial to analyse the factors influencing energy consumption in sectors like manufacturing, mining, and construction. This chapter analyzes the primary factors influencing energy consumption in Algeria's non-energy industrial sectors, investigating trends, contributing elements, and their consequences for sustainable development. The study identifies these drivers to offer insights for policymakers, enhancing energy efficiency and supporting the transition to a more diversified and resilient economy.

3.2 Decomposition analysis of non-energy industry

The LMDI method is based on the concept of the logarithmic mean function, which ensures a complete decomposition of changes in an aggregate indicator (such as energy consumption or CO_2 emissions) into its contributing factors without residual errors [39]. The LMDI approach is often categorized into two forms (figure 3.1):

LMDI-I (Additive Decomposition)**:** Expresses total change as the sum of contributions from different factors.

LMDI-II (Multiplicative Decomposition)**:** Expresses changes as a product of factor contributions.

Ang developed the LMDI framework and demonstrated its superiority over other index decomposition methods, such as the Laspeyres and traditional Divisia indices, due to its consistency in factorization, ease of interpretation, and ability to handle zero values [40].

The data resource on energy consumption was taken from reports published by the Algerian Ministry of Energy, and the data source for value added was obtained from the National Office of Statistics in Algeria in the past years between 2002 and 2021 [9, 22]. The present study pertains to the energy consumption data of nine distinct energy resources, including electricity, natural gas, coke, charcoal, coke oven gas, liquefied petroleum gas, gasoline, diesel oil, kerosene and other petroleum products, within each non-energy industry over a period of 19 years. The LMDI approach identifies three main effects (structural effect, energy intensity effect, and activity effect) to drive the change in total energy consumption in different sub-sectors.

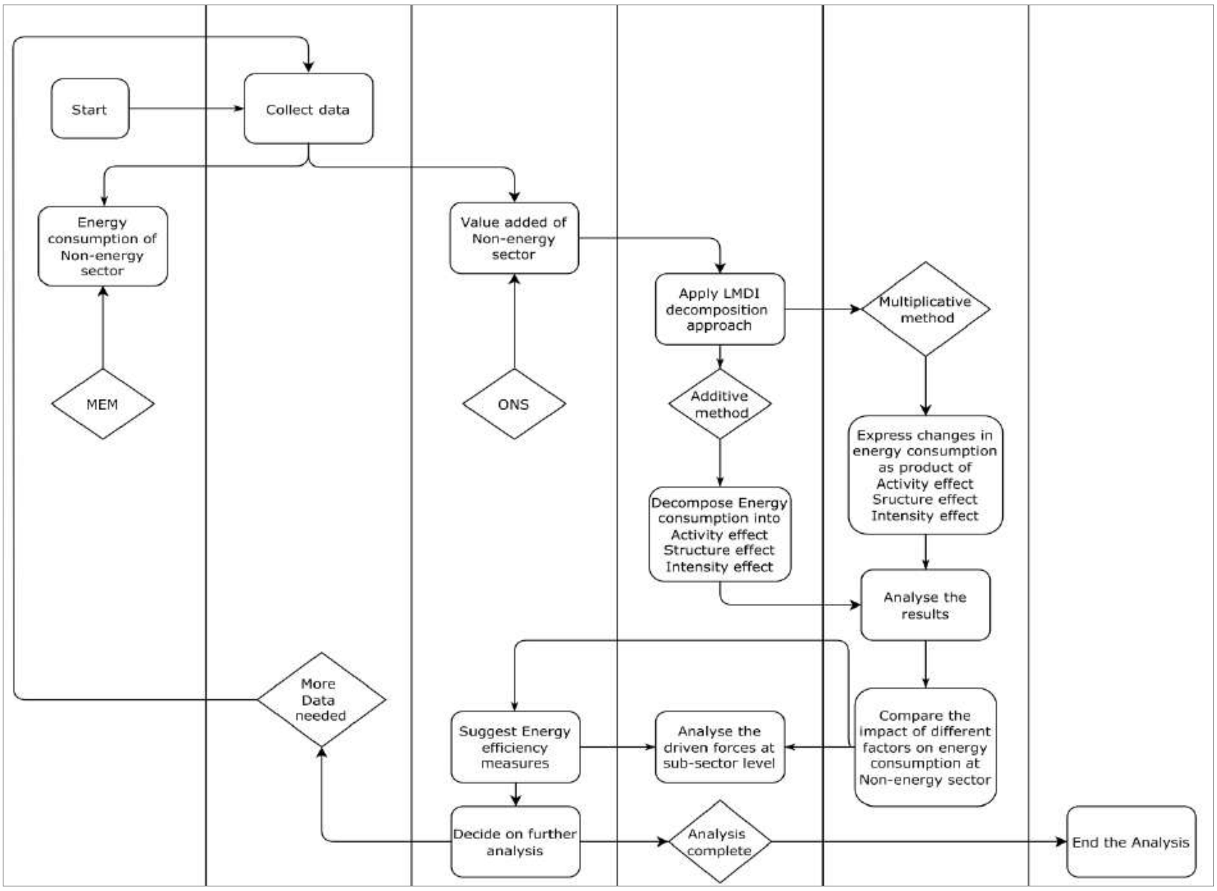

Figure 3.1 Additive and Multiplicative decomposition analysis of Algeria's non-energy industries.

The following is the formula for the general index decomposition analysis, developed by Ang [41], who has divided an aggregate V into n factors and i sub-sector:

$$V = \sum_i V_i = \sum_i X_{1,i} X_{2,i} X_{3,i} \dots X_{n,i} \qquad (1)$$

Where $X_{n,i}$ denotes the factor influencing the change in energy consumption in 'i' subsectors.

$$D_{tot} = V_t / V_0 = D_{X1} D_{X2} D_{X3} \dots D_{Xn} \qquad (2)$$

The basic equation of LMDI can be expressed in the following form:

$$D_{ij} = \exp(\sum_i \frac{L(V_i^t, V_i^0)}{L(V_t, V_0)} \ln\left(\frac{X_{j,i}^t}{X_{j,i}^0}\right) \qquad (3)$$

$$L(\alpha, \beta) = \frac{\alpha - \beta}{\ln\left(\frac{\alpha}{\beta}\right)} \qquad (4)$$

where "j" represents energy source and L is the logarithmic average of two positive numbers α and β.The additive decomposition can be expressed via following equations [41]:

$$\Delta E_{tot} = \Delta E_{act} + \Delta E_{srt} + \Delta E_{int} = E^{T} - E^{0} \quad (5)$$

$$\Delta E_{act} = \sum_{i}^{n} \frac{\Delta E_i^T - \Delta E_i^0}{ln\Delta E_i^T - ln\Delta E_i^0} \ln(\frac{Q^T}{Q^0}) \quad (6)$$

$$\Delta E_{str} = \sum_{i}^{n} \frac{\Delta E_i^T - \Delta E_i^0}{ln\Delta E_i^T - ln\Delta E_i^0} \ln(\frac{S_i^T}{S_i^0}) \quad (7)$$

$$\Delta E_{int} = \sum_{i}^{n} \frac{\Delta E_i^T - \Delta E_i^0}{ln\Delta E_i^T - ln\Delta E_i^0} \ln(\frac{I_i^T}{I_i^0}) \quad (8)$$

$$E = \sum_{i} E_i = \sum_{i} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_{i} Q S_i I_i \quad (9)$$

$$S_i = Q_i/Q \quad (10)$$

$$I = E/Q \quad (11)$$

Where, ΔE_{tot} is the total energy index from year 0 to year t.

ΔE_{act} activity effect (act), that is related to variations in the amount of economic activity or the overall output level of the economy. It predicts that an increase in the output level leads to a correspondent increase of energy consumption.

ΔE_{srt} structural effect, that is related to alterations in the combination of activities that are taken into account. While the different actions require the different quantities of energy to be consumed, such changes influence the overall energy consumption.

ΔE_{int}intensity effect , that is considered as the influence of the changes in energy intensity on energy consumption. The energy intensity reductions can be attributed by either the enhanced technological efficiency or the improved processes.

I_i , and S_i represents the energy intensity and the production share of the sub-sector i, respectively.
$E$and Q represents the total energy consumption in the industry and the value added of the non-energy industry output at 1989 constant prices (billion AD), respectively.

The LMDI multiplicative factor decomposition analysis is presented by the following equations:

$$D_{tot} = D_{act} \times D_{srt} \times D_{int} = \frac{E_t}{E_0} \tag{12}$$

$$D_{act} = \exp \sum_{i}^{n} \left[\frac{L[E_i^T, E_i^0]}{\sum_i^n L[E_i^T, E_i^0]} \ln \frac{Q_t}{Q_0} \right] \tag{13}$$

$$D_{srt} = \exp \sum_{i}^{n} \left[\frac{L[E_i^T, E_i^0]}{\sum_i^n L[E_i^T, E_i^0]} \ln \frac{S_{i.t}}{S_{i.0}} \right] \tag{14}$$

$$D_{int} = \exp \sum_{i}^{n} \left[\frac{L[E_i^T, E_i^0]}{\sum_i^n L[E_i^T, E_i^0]} \ln \frac{I_{i.t}}{I_{i.0}} \right] \tag{15}$$

(D_{tot}) between period of 0 and t years through the evaluation of the individual contributions made. The utilization of the multiplicative factor decomposition facilitates the analysis of the overall increase in energy consumption by the activity effect (D_{act}), structure effect (D_{str}), and intensity effect (D_{int}).The theoretical relationship between the multiplicative and additive factor decomposition is determined by Equation (16).

$$\frac{\Delta E_{tot}}{\ln D_{tot}} = \frac{\Delta E_{act}}{\ln D_{act}} = \frac{\Delta E_{str}}{\ln D_{str}} = \frac{\Delta E_{int}}{\ln D_{int}} \tag{16}$$

The additive decomposition of energy consumption in non-energy industries from 2002 to 2021 is illustrated in Figure 3.2. In Algeria, non-energy industries have had a 7316 ktoe rise in energy use during the past 19 years. During this time, the non-energy sector's energy consumption increased significantly by 527.93% due to the impact of activity change. On the other hand, the aggregated energy consumption decreased by 62.76% due to structural effects and 76.08% due to intensity effects.

The findings were examined in light of current studies on energy consumption of different types of industries in different countries. Research has shown that economies of scale lead to decrease specific energy consumption in industrial sectors with growing production capacity [41]. Key aspects include the energy consuming units involved in value creation within production chains, which have a considerable impact on the scaling effect. This influence varies among industrial subsectors and between Europe and the United States, emphasizing the importance of understanding these dynamics in promoting energy efficiency and cleaner energy transitions. In France's industrial sector, the structural effect was identified as the most dominant factor (75%) in improving energy performance between 1996 and 2005 [42]. The analysis supports the development of a detailed bottom-up techno-economic energy model for the non-energy industry to assess global energy efficiency and CO_2 emissions reduction potential, particularly in heat recovery with heat pumps. The impact of industrial activity in Algeria emphasizes the difficulties in integrating industrial growth with energy sustainability. The structural and intensity effects demonstrate the capacity for policy interventions to improve energy efficiency and promote transitions to less energy-intensive industries.

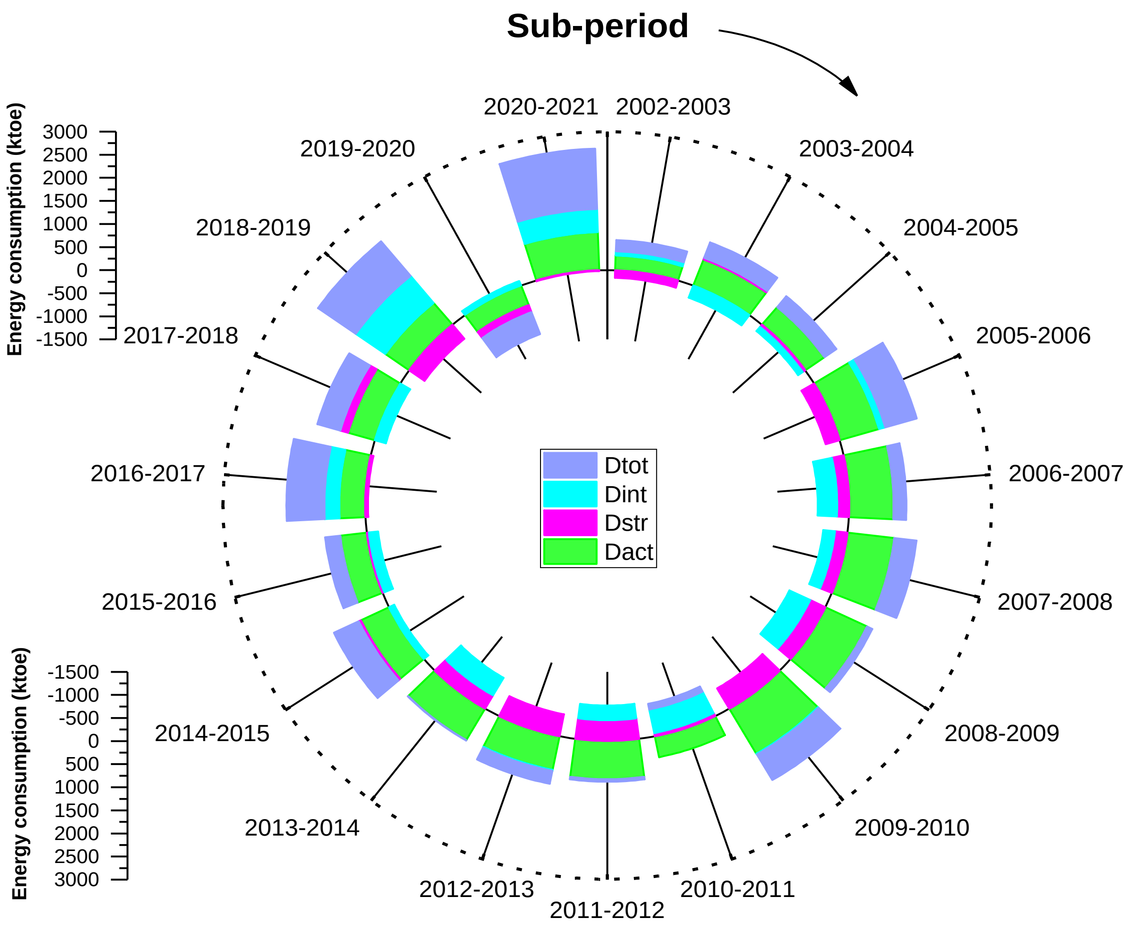

Figure 3.2 Additive decomposition of energy consumption in non-energy industries from 2002 to 2021.

3.2.1 Construction materials Industry

Figure 3.3 illustrates additive and multiplicative decomposition analysis of "construction materials" subsector within the period of 2002-2021. The energy consumption of the "construction materials "industry has increased from 1729 ktoe to 4887 ktoe between 2002 and 2021. The "construction materials" sub-sector is the industry that has contributed the most significant activity effect, followed by "iron and steel, mechanical, electronic and electric equipment", "food products, beverages, and tobacco," and "construction and public works". The industry with the largest contribution to decrease the energy consumption due to the intensity effect is the subsectors including "construction materials", "iron and steel, mechanical, electronic and electric equipment "industries The structural effect contributes to a decrease in energy consumption within the "construction materials" and "other industries".

The "construction materials "industry has seen to hold a large share of the total change in energy consumption for the whole non-energy industry during (2002–2021) (see in figure 3.3a), accounted for 3158 ktoe. The positive impact of activity leads to a substantial increase in the overall energy consumption, reaching a total of 5056.88 ktoe. However, the structural and intensity impacts have led to reduce the energy consumption of 1164.33 ktoe and 734.54 ktoe, respectively. Conclusively, these data serve as credible indications of the progress made to improve the energy efficiency [22].

The multiplicative decomposition analysis has shown the increase in energy consumption of the "construction materials" sub-sector is largely due to the activity effect (see in figure 3.3b). The intensity effect has been found to have a significant impact on the rise in energy consumption within the "construction material" industry throughout the sub-periods of (2002-2003), (2009-2010), (2015-2016), (2016-2017), (2018-2019) and (2020-2021), whereas a decline of energy consumption has been tracked from the remaining sub-periods. The structural effect was shown to have an important effect on the reduction of the energy consumption throughout all sub-periods, except for the periods between 2003-2004, 2014-2015, 2017-2018 and 2019-2020 due to a low energy usage.

China's construction materials sector identified the activity effect as the principal determinant of energy consumption, although enhancements in energy efficiency and structural modifications contributed to the reduction of energy consumption [43]. The energy-efficient technologies, including waste heat recovery and alternative fuels, emphasis the capacity to diminish energy intensity in cement manufacturing [44]. The material substitution and lightweight construction methods play significance role in diminishing energy consumption within the construction sector [45]. The current study emphasis on sub-period changes and detailed research of the "construction materials" subsector offers a more refined comprehension of the underlying causes and mitigation techniques involved.

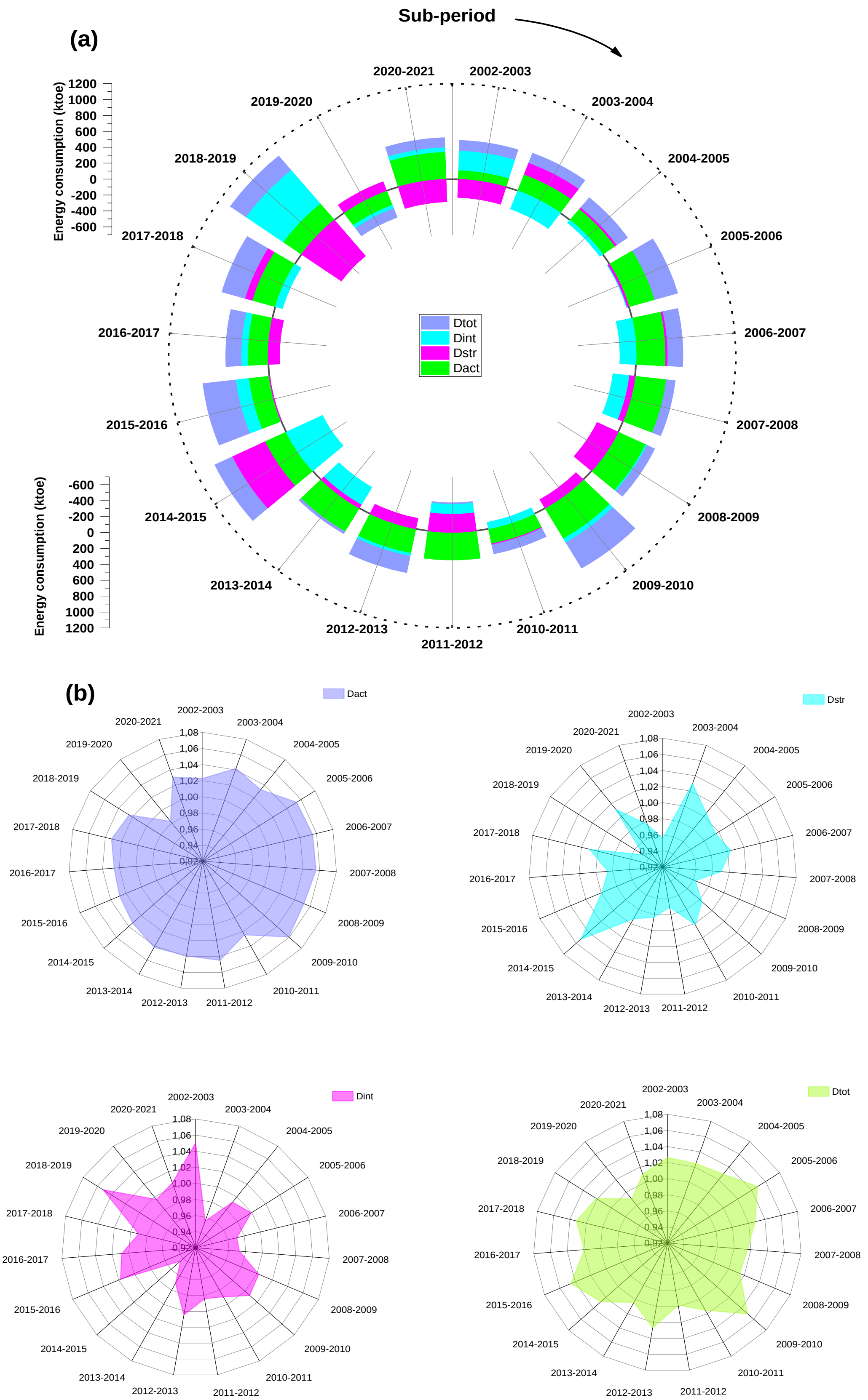

Figure 3.3 (a) Additive and (b) multiplicative decomposition of energy consumption in construction materials industry from 2002 to 2021.

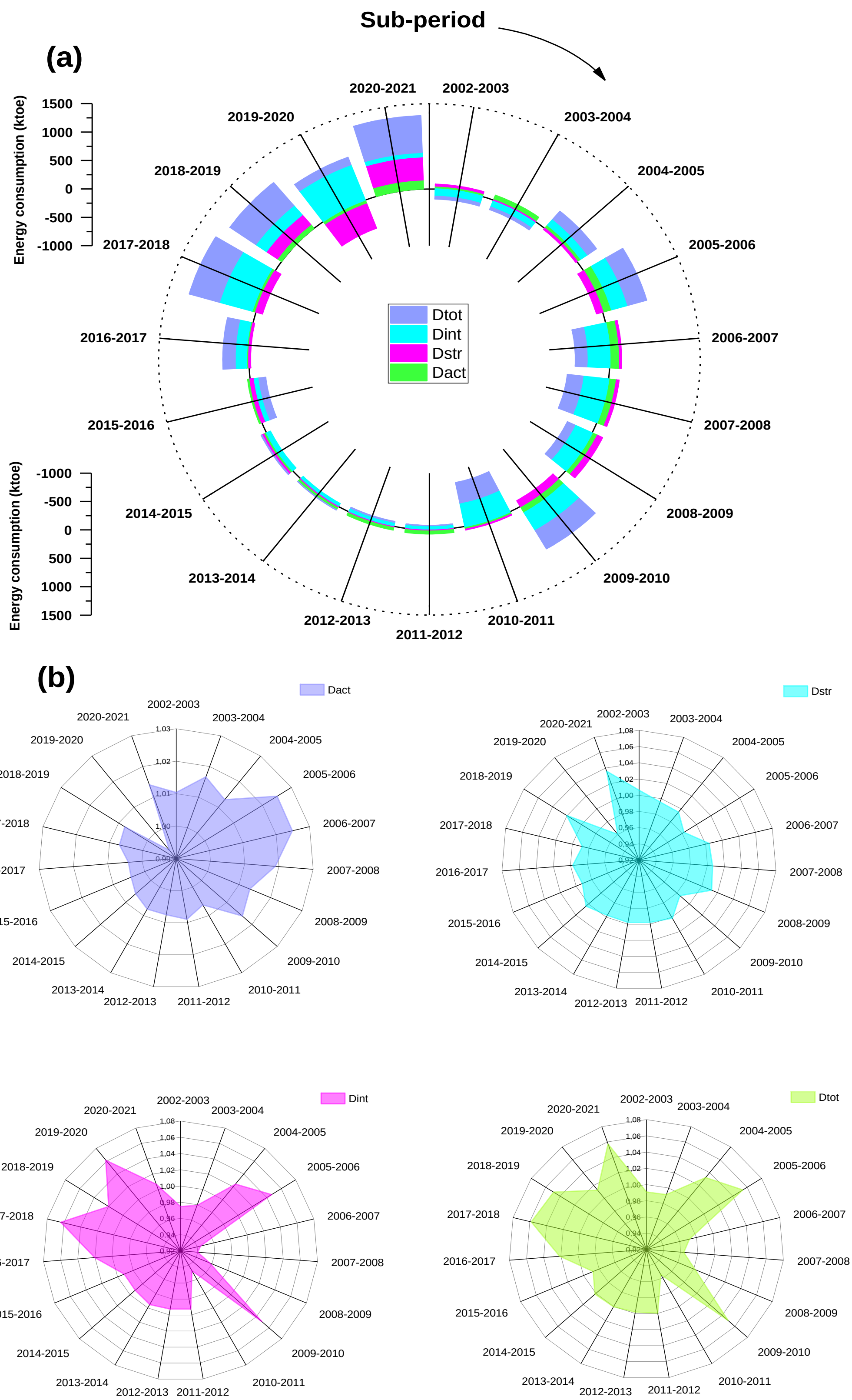

Figure 3.4 (a) Additive and (b) multiplicative decomposition of energy consumption in "iron and steel, mechanical, electronic and electric equipment" industry from 2002 to 2021.

3.2.2 Iron and Steel, Mechanical, Electronic and Electric Equipment Industry

According to reports from the National Office of Statistics, the value added of the "iron and steel, mechanical, electronic and electric equipment" subsector has increased from 34.31 billion DA in 2002 to 136.77 billion DA, representing a growth of 298.37% [22]. The sector by following "construction materials" industry for energy consumption is the "iron and steel, mechanical, electronic and electric equipment" subsectors. The data analysis has explored a significant impact of the intensity effect on the energy consumption patterns of the "iron and steel, mechanical, electronic and electric equipment" industry across multiple time periods on a yearly basis from 2002 to 2011 and from 2015 to 2020, respectively (figures 3.4). Between the years from 2011 to 2015, the overall energy consumption had minimal changes, due to the combined effects of structural, intensity, and activity factors.

3.2.3 Chemistry Industry

Petrochemicals, cosmetics, paints, rubber, plastic, and pharmaceutical items in chemistry subsector are just a few products made by the "chemistry" industry [22]. They are commonly supplied to various industries as components or raw materials. Figure 3.5 illustrates that the energy consumption between 2002 and 2021has increased from 267ktoe to 851ktoe due to chemical production. Nevertheless, the data analysis has indicated the contribution of the chemistry industry to aggregate energy consumption in the non-energy sector was weak because of contracting effects of production during the period of 2002 to 2021.

As shown in figures 3.5 for the years from 2008–2009 and from 2011–2012, respectively, the activity impact is responsible for the increase of the aggregating energy consumption in the chemistry industry. The intensity effect has contributed to a 3.65% increase in energy consumption from 2020 to 2021. However, the energy consumption has been relatively stable on an annual basis for the sub-years from 2002 to 2021, except for the sub-periods from 2017 to 2018 and 2020 to 2021. It is worth to note that during the remaining sub-periods, the activity effect, the structural effect, and the intensity effect all have shown the tendency in opposite directions.

The trends in energy consumption within the chemical industry illustrate the intricate interaction of activity, structural, and intensity effects. Although increased industrial activity has propelled energy consumption during specific periods, advancements in energy efficiency and structural modifications have contributed to the stabilization of overall energy use [22]. Nevertheless, external influences, such as the COVID-19 pandemic, have slightly interrupted these trends, emphasizing the requirement for effective and sustainable energy policies [46, 47].

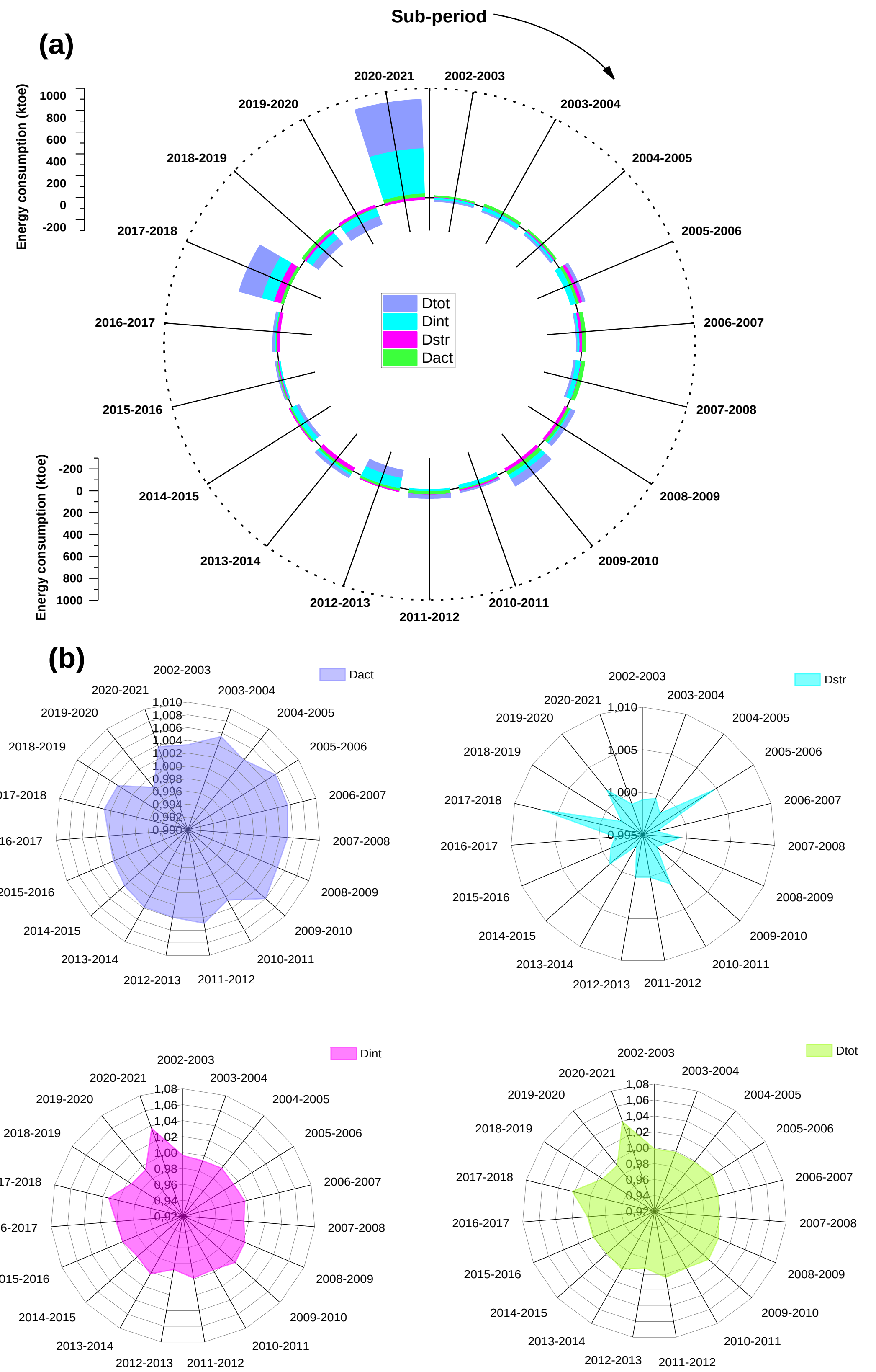

Figure 3.5 (a) Additive and (b) multiplicative decomposition of energy consumption in chemistry industry from 2002 to 2021.

3.2.4 Food, beverage, and tobacco Industry

In 2021, the total value added of non-energy industry in the "food, beverage, and tobacco" sub-sector was 14%, according to the National Office of Statistics. Figure 3.6 depicts the positive effect of the intensity change on the "food products, beverages, and tobacco" industries from 2005–2006, and 2010-2011, and the negative effect from 2009-2010 and 2014-2015, respectively. The negative impact on activity occurred from 2019 to 2020, although it led to an increase in energy consumption throughout the remaining sub-periods. The period spanning from 2019 to 2020 experienced a detrimental effect on activity, possibly attributable to the COVID-19 pandemic, which disrupted global supply networks and diminished demand for non-essential commodities [48, 49]. Nonetheless, energy consumption increased throughout other sub-periods, indicating inefficiencies or enhanced efficiency in production. The energy intensity in China's food processing industry fluctuated significantly as a result of technology innovations and policy modifications [50]. Likewise, the adverse consequences observed during 2019–2020 might be compared with the pandemic's disruptive influence on global manufacturing industries [51].

3.2.5 Textile, clothing, and leather Industry

The "textile, clothing, and leather" subsector comprises basic textiles, apparel, leather goods, and footwear. In 2021, around 33.67 billion Algerian dinars, adjusted to constant 1989 prices, were produced in the "textile, clothing, and leather" sub-sector [22]. Figure 3.7 illustrates that the energy consumption between 2002 and 2021 has increased from 77 ktoe to 136 ktoe due to production in "textile, clothing, and leather" industry. This increase can be attributed to multiple factors, including production growth that enhanced capacity and output, consequently raising energy demand; technological advancements, as the implementation of modern machinery and equipment, while augmenting productivity, may also lead to higher energy consumption; and heightened industrial activity, driven by increased domestic demand and export prospects. Although this increase, the industry's energy consumption continues to be the lowest among all sub-sectors, indicating it is comparatively less energy-intensive than other sub-sectors.

This is probably attributable to the characteristics of textile and leather manufacturing, which often entails minimal heavy machinery and reduced thermal energy needs, rendering it intrinsically less energy-intensive than other resource-demanding sectors. The research conducted by Ozturk et al. revealed that energy consumption in the textile sector increased due to heightened output and mechanization [52]. Nevertheless, the current study indicates that enhancements in energy efficiency may reduce this current pattern, potentially clarifying why Algeria's textile sector exhibits comparatively low energy consumption [22].

3.2.6 Construction and public works Industry

After a decade of high development supported by large state investments, the "construction and public works" begin to stabilize, according to the data released by office of national statistics. By 2021, the value added of "construction and public works" by referring the constant 1989 prices had risen from 369.9 billion DA in 2002 to 2455.37 billion DA [22]. This growth shows the sector's vital contribution to Algeria's economic advancement, especially in development of infrastructure including housing, roadways, and public facilities. As shown in figure 3.8, the additive decomposition analysis conducted on sub-periods from 2009 to 2013, 2016 to 2017 and from 2019 to 2020 indicates that the impact from negative intensity has played a significant role in reducing the energy consumption. Moreover, the "construction and public works" has shared a positive activity effect on energy consumption during the remaining sub-periods. Zhou et al., conducted a study on energy efficiency in China's construction sector, revealing that advances in technology and more stringent energy policies markedly decreased energy intensity [53]. Likewise, Algeria's "construction and public works" sector may have gained from comparable innovations or legislative initiatives during these times [22]. Research by Apurv et al. on infrastructure development in Brazil, Russia, India, China and South Africa (BRICS) countries, emphasized that public investments in construction and public works might promote economic growth while simultaneously increasing energy consumption [54]. The influence of governmental investments on the growth of the industry is a prevalent subject in developing economies; Algeria's experience reflects the pattern, as state-led initiatives stimulate economic activity and energy demand. The negative intensity effect shown during 2019–2020 may indicate the repercussions of the COVID-19 epidemic, which interrupted construction efforts worldwide. Majumder ang Biswas suggested that the pandemic diminished energy consumption in the construction sector due to project delays and decreased industrial activity [55]. The construction sector in Algeria probably saw similar issues during this period [22]. The beneficial impact of activities in other sub-periods highlights the necessity for sustainable practices within the building industry. The implementing green building technology and renewable energy sources is crucial to reduce the environmental effects of construction activities. Algeria could gain from incorporating such approaches to harmonize progress with sustainability [56].

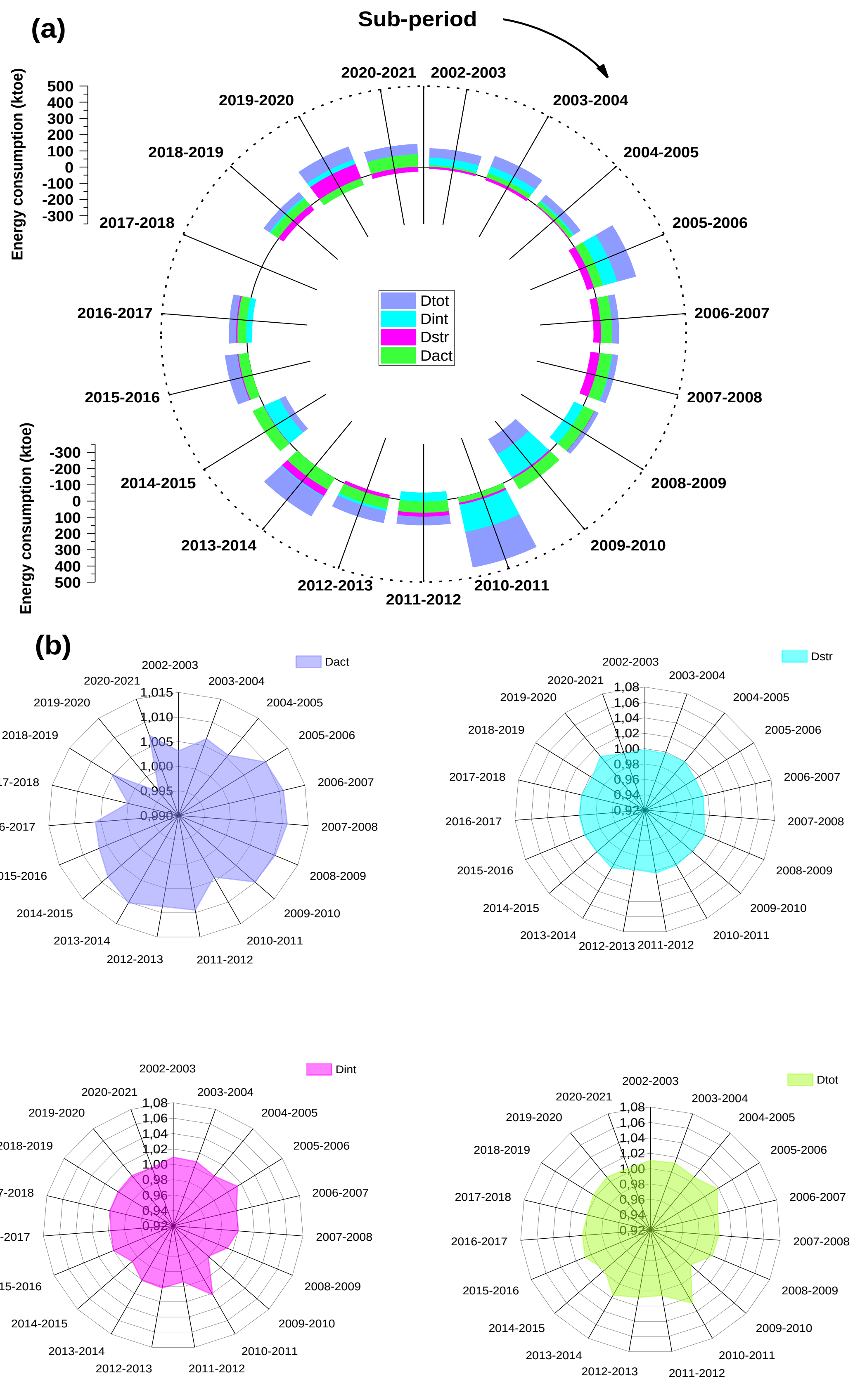

Figure 3.6 Additive and (b) multiplicative decomposition of energy consumption in "food products, beverages and tobacco" industry from 2002 to 2021.

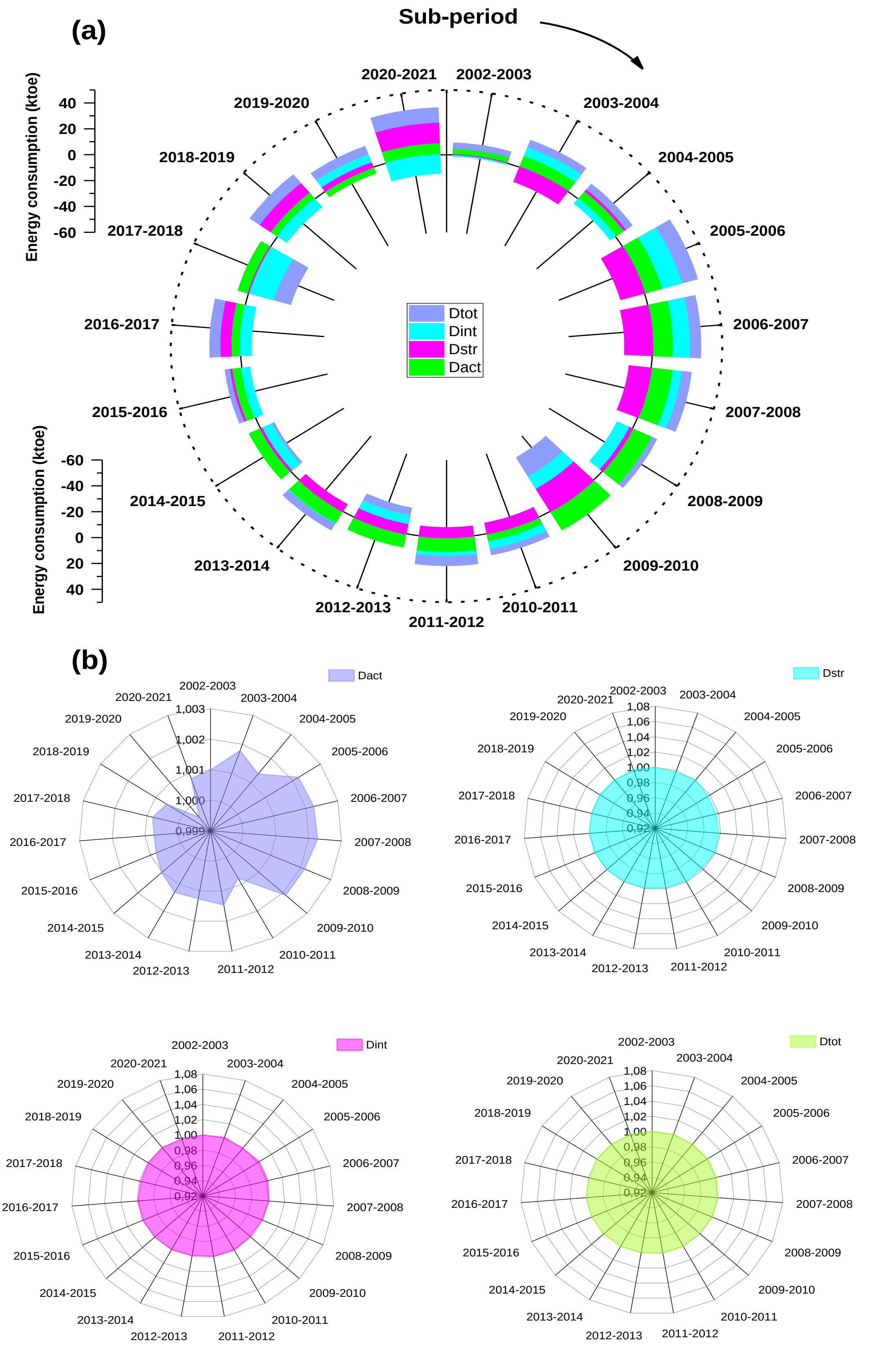

Figure 3.7 (a) Additive and (b) multiplicative decomposition of energy consumption in "textile, clothing and leather" industry from 2002 to 2021.

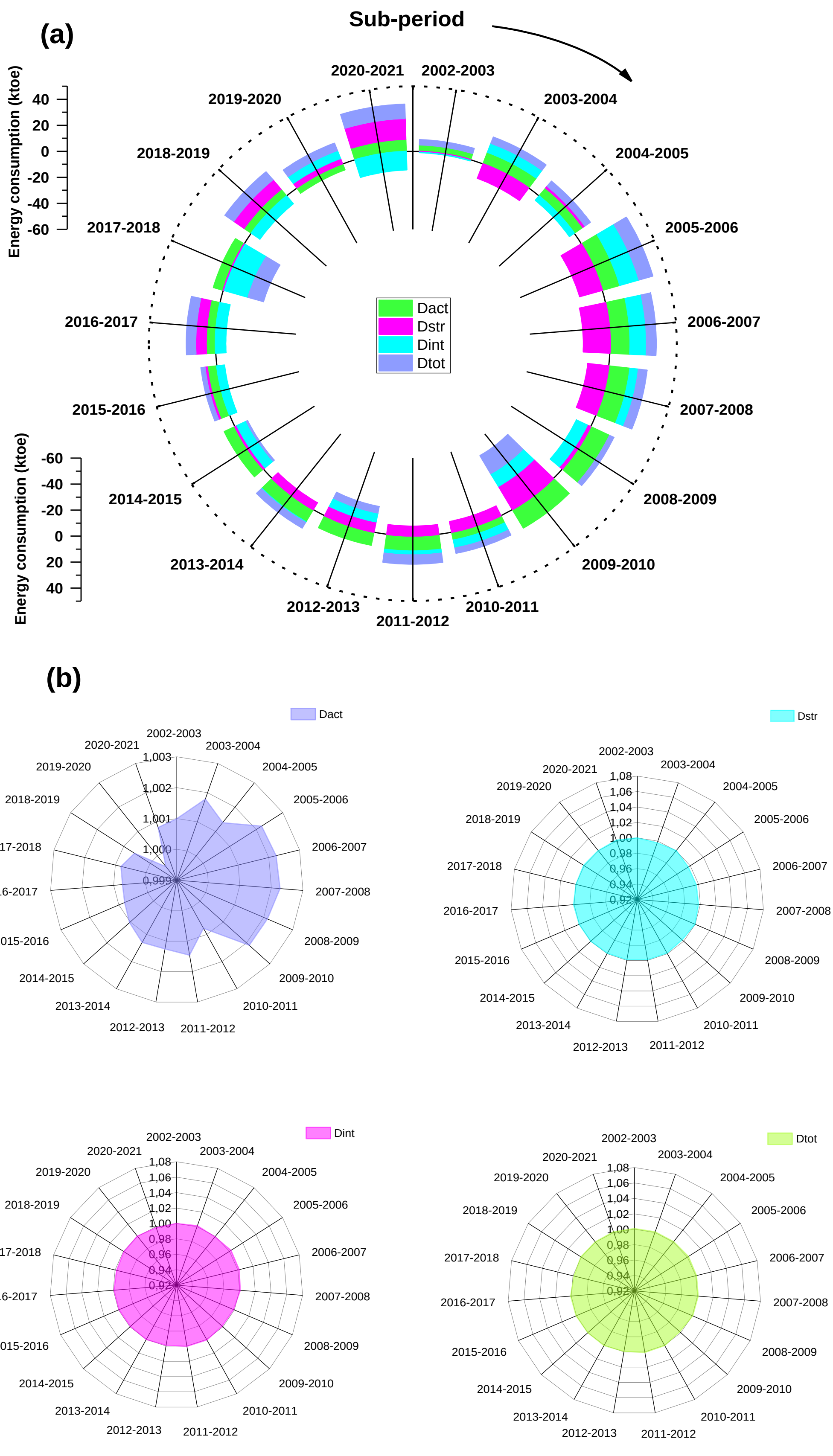

Figure 3.8 (a) Additive and (b) multiplicative decomposition of energy consumption in "construction and public works" industry from 2002 to 2021.

3.2.7 Other industries

The "other industries" subsector encompasses all the remaining non-energy-specific industries, including the furniture, wood, veneer, cork, and paper material sectors [22]. In 2021, energy consumption in these industries has increased by 777 ktoe compared to 2002 (figure 3.9 a). This increase can be attributed to a 138.09% rise in activity levels and a 106% rise in energy intensity. The structural effect has significantly reduced energy consumption by 78.63% (figure 3.9 b). The data trends displayed in Figure 15 demonstrate a drop in energy consumption during the sub-periods of 2004 to 2006, 2009 to 2010, 2013 to 2014, 2015 to 2016 and 2017 to 2020. The decline was attributed by the combined effects of negative intensity and structure

Implementing changes to industrial strategies based on these results can increase the energy efficiency of all non-energy subsectors and lead to a sustainable economy. By applying the decomposition framework method, it becomes clearer how non-energy industries have increased their energy efficiency [57, 58]. The energy intensity in China's industries indicates that enhancements in energy efficiency and structural changes have significantly decreased energy intensity over time [59]. The increase in energy intensity within Algeria's "other industries" subsector diverges from global patterns observed in numerous industrialized countries, where energy intensity has been decreasing as a result of technological innovations and policy changes.

The positive structural effect identified in Algeria corresponds with findings from various other countries. The Middle East and North African industries, emphasizing the significance of structural changes in minimizing energy consumption, especially within the wood and paper production sectors [60]. This indicates that Algeria's subsector may gain from additional structural optimisation. Energy consumption declines in specific sub-periods, notably 2009–2010 and 2017–2020, likely indicate the effects of economic crises, including the global financial crisis and the COVID-19 pandemic [61]. The International Energy Agency reported that economic downturns typically result in temporary declines in industrial energy consumption, attributed to reduced production levels [3]. The findings underscore the necessity of modifying industrial strategies to enhance energy efficiency. This is in accordance with the outcomes of the implementation of energy-efficient technologies and practices is essential for attaining sustainable industrial growth [62].

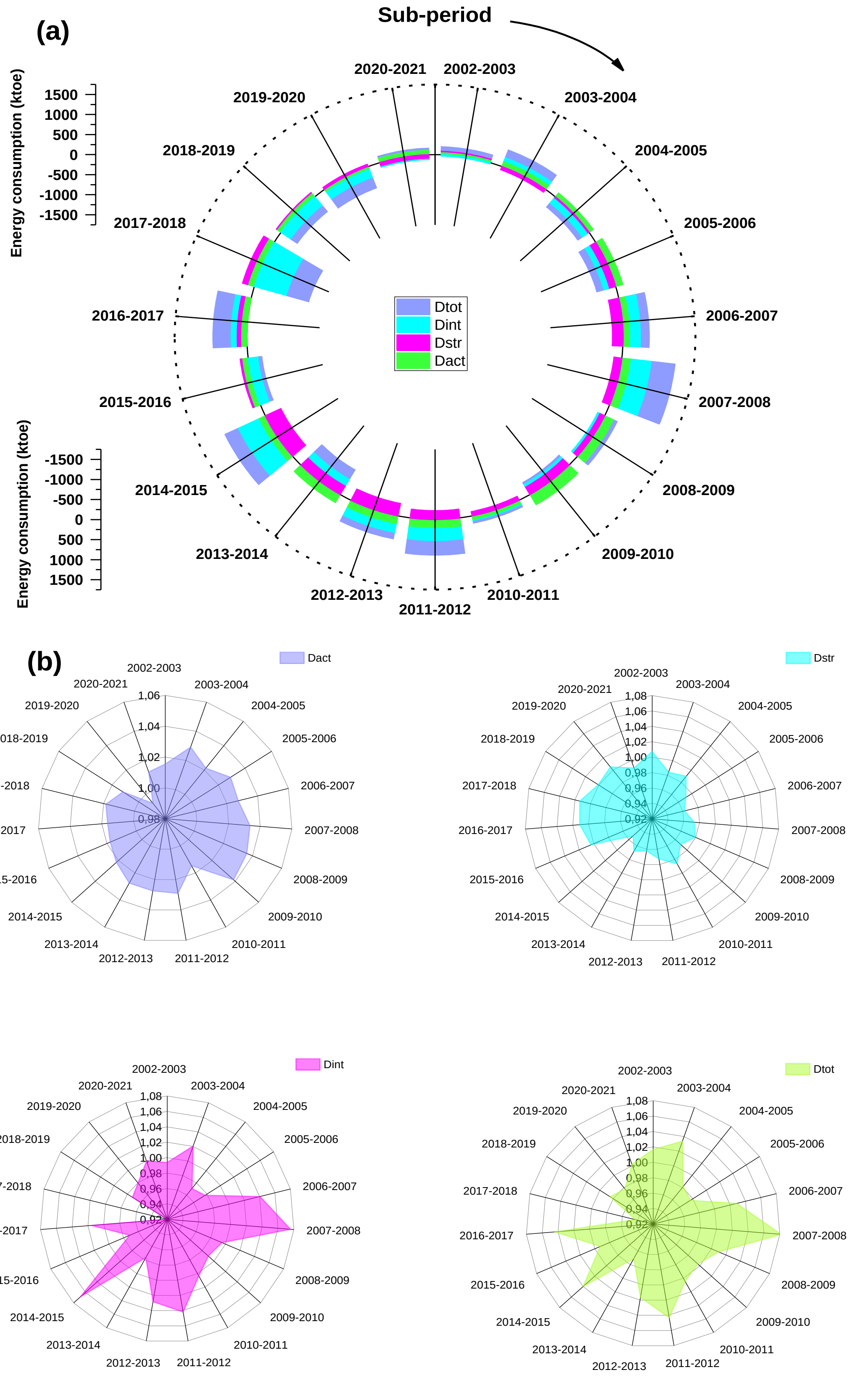

Figure 1.9 (a)Additive and (b) multiplicative decomposition of energy consumption in "other industries" from 2002 to 2021.

4. Conclusions

The evolution of energy consumption in energy sector has reflected the increase of the on-going development to weight on the economic growth in Algeria. By analysis of energy consumption, the non-energy industry sector has frequently been overlooked. To understand the landscape of energy consumption, we have conducted an analysis of the non-energy industry sector in Algeria using the LMDI technique that has only been developed for energy performance analysis in recent years. The outcomes of this study have provided the essential but important information that emphasizes the importance of the non-energy sector's contribution to the energy consumption, aimed at facilitating the exploitation of methods to decrease the energy consumption owing to the reduction of the production costs and boost the competitiveness and productivity of this sector.

Chapter 04

CO_2 Emissions in Algeria’s Non-Energy Industries: Trends, Key Drivers, and Mitigation Strategies

4.1 Introduction

The rise CO_2 emissions from Algeria's non-energy industries provide a major environmental and political challenge. Although the energy sector still accounts for the majority of the nation's carbon footprint, non-energy sectors have seen consistent emissions increase from industrial growth, higher output, and relying on carbon-intensive activities. The objective of this chapter is to identify and analyze the forces driving CO_2 emissions changes in non-energy industries. It will also address the patterns in CO_2 emissions throughout various subsectors. Algerian policymakers have the opportunity to utilize the empirical findings to develop sustainable energy strategies, especially for the non-energy sectors, thereby enhancing the country's potential to achieve its energy and environmental objectives.

4.2 Bibliometric and systematic literature review

The VOSviewer tool organized a bibliometric analysis of 12624 papers published in Elsevier journals and 1008 in Scopus journals, indexed with the keywords "decomposition analysis," "Industry," and "CO_2 emission," up to April 12, 2023, as illustrated in figure 4.1. Studies have used decomposition analysis to determine the factors contributing to energy-related carbon dioxide emissions [63-66]. China, as seen in Figure 4.1, is the most country highly relevant to CO_2 emissions in prior research. Zhang et al., primarily examined the factors that influence China's carbon dioxide emissions, explores the potential for reducing carbon intensity, and considers the various strategies that might be employed to achieve emission reduction targets [67]. Applying the LMDI approach, Lin and Raza [68] investigated the energy-related emissions in Pakistan spanning from 1978 to 2017. It highlights the impact of factors such as population growth, economic expansion, and social activities on CO_2 emissions. The results indicate that changes in population, economic activity, and gross domestic product lead to an increase in CO_2 emissions. However, the effects of carbon intensity and energy intensity have a reducing impact on emissions. Rapid economic growth was accompanied by a persistent increase in both the total and intensity of carbon emissions in India, the world's fourth-largest emitter and the second-largest developing nation [69]. The results indicate Private consumption, investment, and exports were determined to be the primary drivers of India's emissions. According to [70], both emissions and intensity showed annual increases. The impact of structural changes decreased, but the energy intensity specific to each industry increased emissions. The analysis suggests implementing regulations aimed at reducing energy intensity, restricting coal consumption, and minimizing power usage as measures to effectively mitigate CO_2 emissions. Analysis of energy-related CO_2 emissions has received considerable interest as it pertains to developing nations.

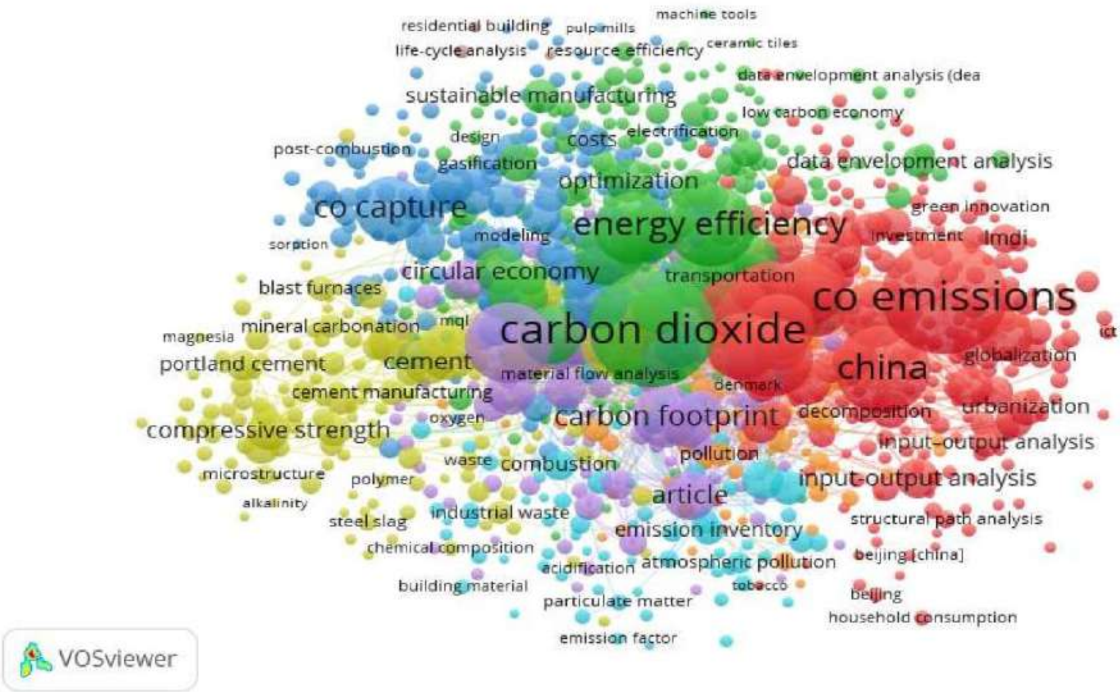

Figure 4.1 Co-word Bibliometric Analysis Using Elsevier and Scopus Databases.

On the other hand, the instance of Algeria has seen very little effort directed towards establishing causal links. Chekouri et al. evaluated the important elements that led to carbon emissions in Algeria between 1971 and 2016 [71]. The study used partial least squares regression to evaluate and comprehend the mechanisms driving these emissions. The findings indicate that the CO_2 emissions are positively impacted by population, with energy usage, urbanization, and income being the most notable factors. As mentioned before, there is a wide range of literature available on decomposition analysis in relation to energy consumption and carbon dioxide emissions. However, their impact on the Algerian economy is quite limited. A recent study by Rahmane et al. examines the factors behind the increase in CO_2 emissions in Algeria from 2000 to 2019 [72]. The researchers employed the logarithmic mean division index (LMDI) to analyze these factors. From the findings, it is clear that economic activity has a major impact on the increase of CO_2 emissions. Based on the following study, the decrease in energy efficiency, the transition of the Algerian economy towards energy-intensive sectors, the significant energy intensity, and the structure of the economy all played a role in the inability to lower CO_2 emissions levels. The energy mix factor also contributed to a slight increase in emissions. Research on the non-energy sector requires immediate attention due to the small number of existing literatures on the subject. Alternatively, this study's innovative approach is to model a renewable energy scenario where CO_2 emissions are converted into methanol, which could be a tool for lowering emissions.

Correlation analysis offers important insights for energy and climate policies; however, some critics contend that it fails to completely quantify the influence of contributing variables. Decomposition analysis serves as a commonly employed methodology that addresses this issue.

4.3 Global overview of CO_2 emissions

CO_2 emissions have been a major contributor to global climate change. The cumulative anthropogenic releases of CO_2 to the atmosphere reached 2400 Gt CO_2 by the end of 2021[3]. Since the industrial revolution, emission time series have shown a steep increase, especially following major historical eras: the United States' emergence as the first industrial power during the early 1900s, the energy transition of the West during the post-World War II era, the restructuring of the economy in Eastern European countries, and the rapid urbanization and industrialization of China [64] [67]. Recently, emissions from countries such as India, Brazil, and Indonesia have increased significantly, contributing to the shifting of the global emission dominance from the West to East Asia [3]. Following the climate negotiations in Kyoto, Japan in 1997, almost all countries adopted the United Nations Framework Convention on Climate Change (UNFCCC) in an effort to mitigate climate change. During this voluntary agreement, industrialized nations committed to reducing their greenhouse gas emissions by 5.2% from 1990 levels by 2012. For many developing countries, initially, the participation of the UNFCCC was a common option for climate policies. Until approximately 2007, the global response to climate change remained uneven. While some developing countries acknowledged the urgent need for climate policy, others continued to hesitate or even oppose engagement with the emerging climate governance framework. Several countries, such as Nigeria and various countries in the Middle East, maintained that climate change had been predominantly caused by industrialized Western countries, and hence, the obligation for mitigation should primarily, if not only, lie with their governments [13] [61] [65]. This position persisted despite the rapid economic expansion and increasing CO_2 emissions observed in many of these developing economies.

4.4 Overview of CO_2 emissions in Algeria

As seen in figure 4.2, Algeria, alongside Egypt, has emerged as the second largest contributor to CO2 emissions exceeded 178 million tons (Mt) among the countries in North Africa. Algeria's non-energy industrial sector holds significant importance in terms of economic stability and CO_2 emissions. The non-energy industrial sector of Algeria is responsible for more than 50 million tons of total CO_2 emissions [11]. It mainly consists of non-metallic mineral products, the chemical sector, basic metals production, refining, and the "other industries" group, which consists mainly of food processing and metallurgy. The 2000s were characterized by the rapid development of the non-energy industries sector, mainly cement and phosphoric acid products, which are expected to continue.

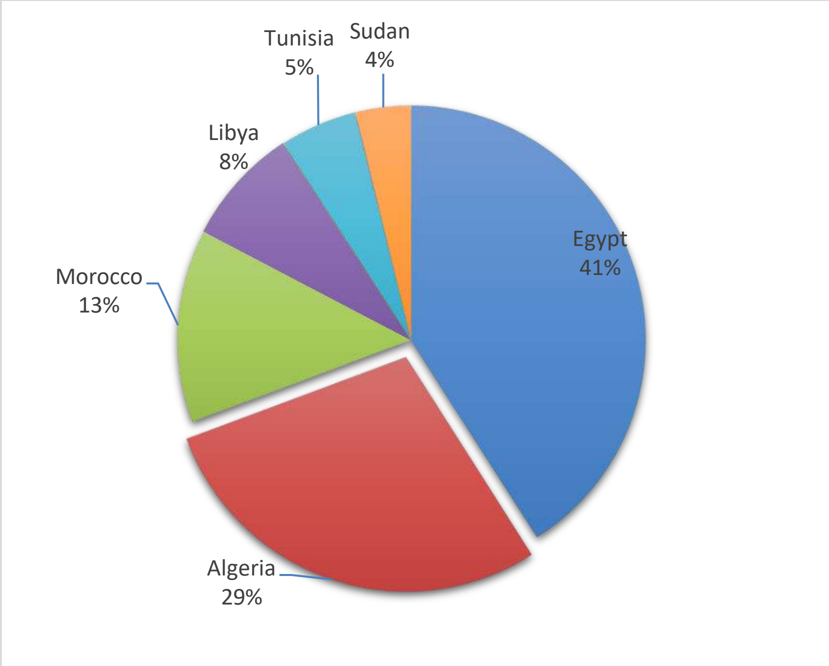

Figure 4.2 CO_2 emissions in North Africa countries, 2021.

The alarming rise in CO_2 emissions could remain unmitigated unless concrete actions are taken, even when accounting for a 75% potential emission reduction. This primarily has to do with the cement industry's competitiveness, but also with the fact that energy efficiency in the chemical sector could generate small reductions with efficiency measures being implemented on existing technologies. Decisive and consistent implementation of decarbonization strategies is urgently needed. Shift towards less carbon-intensive cement production is the most viable measure in Algeria's decarbonization strategies. Improvement of energy consumption in clinker production could partly be achieved through installation of grate coolers and more efficient pre-heaters, while chemical measures include increasing the use of fly-ash and limestone in cement production [6].

The basic metals sector has a potential of a few million tons emission reductions through energy efficiency measures, carbon capture and exploitation, and hydrogen as a reduction agent [7]. All of the abatement measures are several steps further down the line as compared to those of the cement industry and huge investments would be necessary to reap their potential. A first step in this direction would be the establishment of a transparent monitoring and reporting system for non-energy industries' emissions. Such a system is absolutely necessary to better understand the industrial sectors' current state and its challenges.

This study utilized multiple official data sources covering the 2006-2021 period:

1) Energy consumption data: Obtained from reports by Algeria's Ministry of Energy [9].
2) Economic data: Industrial value-added statistics from Algeria's National Office of Statistics [22].
3) Algeria's total CO_2 emissions data: Sourced from the American Library Association [73].

4.5 Assessing CO_2 emissions

Algeria is one of the most important CO_2 emitters among developing countries and the third among African countries (figure 4.1). It promised to mitigate the emissions at least 7% by 2030 [74].

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories is an important basis for countries all over the world to account for GHG emissions [75]:

$$Eco_2 = \sum_j E_{ij} \times EF_j \qquad (16)$$

Where Eco_2 is the total emission of carbon dioxide, E_{ij} is the energy consumption of the i sub-sector based on fuel type j, and EF_j represents the CO_2 emission factor of the j fuel type. This study, which covers 19 years and applies to all non-energy industries, focuses on nine energy resources: electricity, natural gas, raw coal, coke oven gas, gasoline, kerosene, diesel, fuel oil, and crude oil.

4.6 Decomposition analysis of energy-related CO_2 emissions

Decomposition analysis has become an effective method for identifying the key sectors and elements that drive energy-related CO_2 emissions. This approach dissects emissions into their individual components, offering a detailed insight into the factors influencing emission patterns. The primary effects that drive the change in total energy related CO_2 emissions in different sub-sectors are identified by the LMDI approach as industrial scale, industrial structure, energy intensity, carbon emission coefficient, and structure effects. The variables used in equations (17–27) are defined in Table 4.1.

Table 4.1 Decomposition variables of equations 17-27

Decomposition parameters	Description
E	Energy consumption in non-energy industry (Ktoe)
Q	value added of non-energy industry output at 1989 constant prices (billion Algerian Dinars)
S_i	production share of the sub-sector i
I_i	energy intensity of sub-sector i (Ktoe/billion AD)
e_{ij}	energy structure of i sub-sector based on j source of energy (ktoe)
R	CO_2 emissions coefficient of energy j consumed by sub-sector i
ΔC_{idscl}	industrial scale effect (kton)
ΔC_{idstr}	industrial structure effect (kton)
ΔC_{eint}	energy intensity effect (kton)
ΔC_{estr}	energy structure effect (kton)
ΔC_{cec}	Carbon emission coefficient effect (kton)
η_{idscl}	contribution ratio of industrial scale
η_{idstr}	contribution ratio of industrial structure
η_{eint}	contribution ratio of energy intensity
η_{estr}	contribution ratio of energy structure
η_{cec}	contribution ratio of emission factor

The Logarithmic Mean Divisia Index decomposition method (LMDI) is used to quantify the energy-related CO_2 emissions change in the Algerian non-energy industry for the period (2006–2021). The energy-related CO_2 emissions decomposition can be expressed in the following equations [76]:

$$\Delta C = \sum_i {Q_i}^t {S_i}^t {I_i}^t {e_{ij}}^t {R_{ij}}^t - \sum_i {Q_i}^0 {S_i}^0 {I_i}^0 {e_{ij}}^0 {R_{ij}}^0 = \Delta Q + \Delta S + \Delta I + \Delta R + \Delta e \quad (17)$$

$$= C^T - C^0 \quad (18)$$

$$\Delta C_{idscl} = \sum_i^n \frac{C_{ij}^T - C_{ij}^0}{lnC_{ij}^T - lnC_{ij}^0} \ln(\frac{Q^T}{Q^0}) \quad (19)$$

$$\Delta C_{idstr} = \sum_{i}^{n} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{0}} \ln(\frac{S_{i}^{T}}{S_{i}^{0}}) \tag{20}$$

$$\Delta C_{eint} = \sum_{i}^{n} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{0}} \ln(\frac{I_{i}^{T}}{I_{i}^{0}}) \tag{21}$$

$$\Delta C_{estr} = \sum_{i}^{n} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{0}} \ln(\frac{e_{i}^{T}}{e_{i}^{0}}) \tag{22}$$

$$\Delta C_{cec} = \sum_{i}^{n} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{0}} \ln(\frac{R_{i}^{T}}{R_{i}^{0}}) \tag{23}$$

$$S_i = Q_i/Q \tag{24}$$

$$I_i = E_i/Q_i \tag{25}$$

$$e_{ij} = E_{ij}/E_i \tag{26}$$

$$R_{ij} = C_{ij}/E_{ij} \tag{27}$$

4.7 Non-energy sector energy consumption and carbon dioxide emissions trends

Figure 4.3 depicts the energy consumption throughout the various sub-sectors and CO_2 intensity of Algeria's non-energy industry from 2002 to 2021. The energy consumption of non-energy industries in Algeria has consistently increased from 6507 Ktoe in 2006 to 12220 Ktoe in 2021, with an average growth rate of 4.39%. In 2021, "construction materials," "food, beverages, and tobacco," and "iron and steel, mechanical, electronic, and electric equipment" industries emerged as the primary contributors to overall energy consumption. The "construction materials" industry showed a significant increase in energy consumption, primarily driven by cement production activities, followed by "food products, beverages, and tobacco" industry. figure 4.3 also shows that the CO_2 emission intensity in the non-energy sector fluctuated between 25.53 Ktons/billion Algerian dinars in 2006 and 14.7 Ktons/billion Algerian dinars in 2021. Emissions of carbon dioxide from energy-related sources in non-energy industries in Algeria rose from 25.92 million tons in 2006 to 50.60 million tons in 2021, at a rate of 4.69 percent per annum. Most important is the fact that energy-related CO_2 emissions from non-energy sources in Algeria have been on the rise, with a peak of 17.82% in 2007–2008, nearly four times the pace of growth seen over the previous decade. In terms of industry contribution, the construction materials industry accounted for the largest share of energy-related CO_2 emissions among non-energy industries in Algeria (33.15%). It was followed by the "other industries" sub-sector (32.66%) and the "iron & steel, mechanical, electronic & electric equipment" industry (12.52%) during (2006-2021).

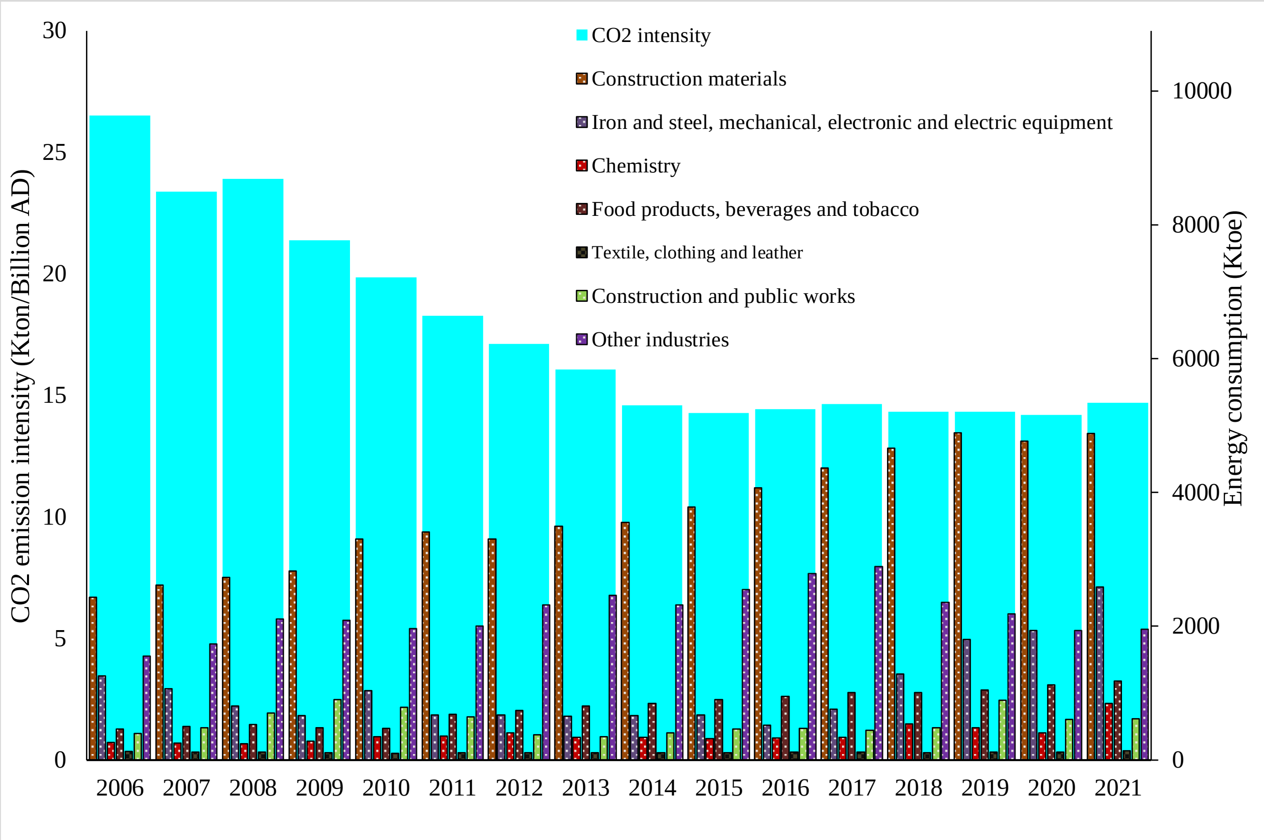

Figure 4.3 Energy Consumption and Carbon Intensity of Non-Energy Industries (2006–2021)

4.8 Analysis of the factors influencing energy-related CO_2 emissions

According to figure 4.4, there was an increase in CO_2 emissions in Algeria's non-energy industries over a 19-year period. The effect of industrial scale is the main driver influencing the increase in carbon emissions, contributing 26.12 Mt, followed by the emission factor effect at 9 Mt. However, the effects of industrial structure and energy intensity take an important part in reducing emissions, accounting for 14.16 Mt and 4.21 Mt, respectively.

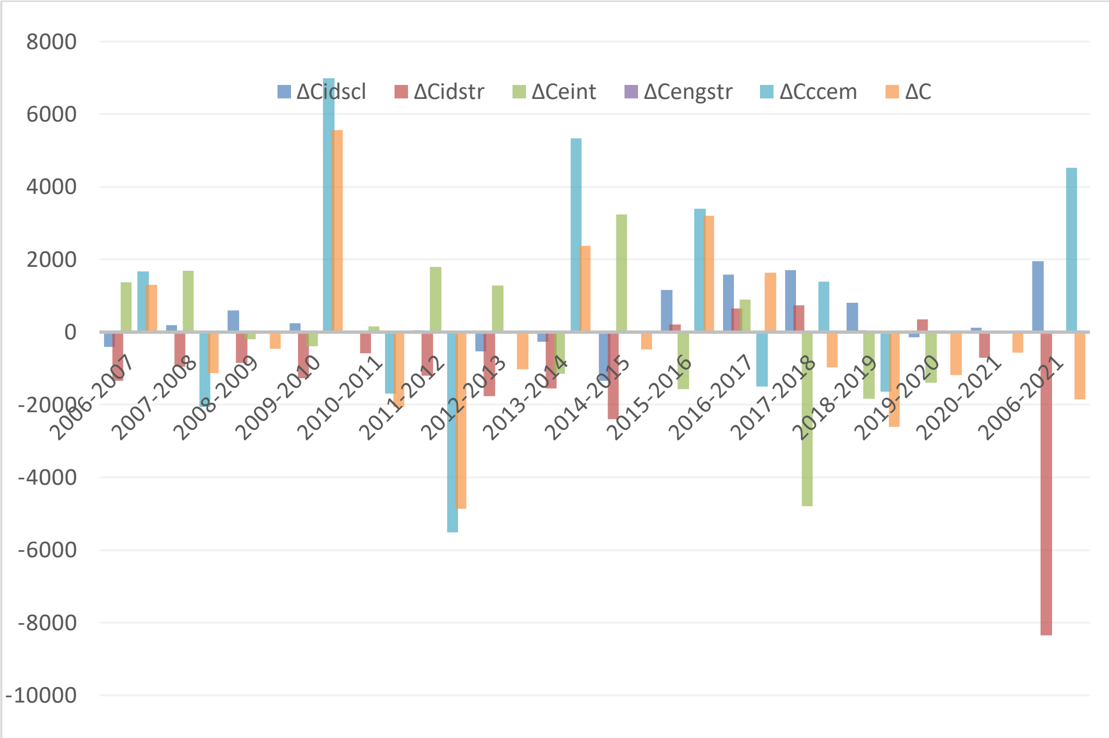

Figure 4.4 Impact of driving forces in non-energy industry by sub-period (Ktons) (2006-2021).

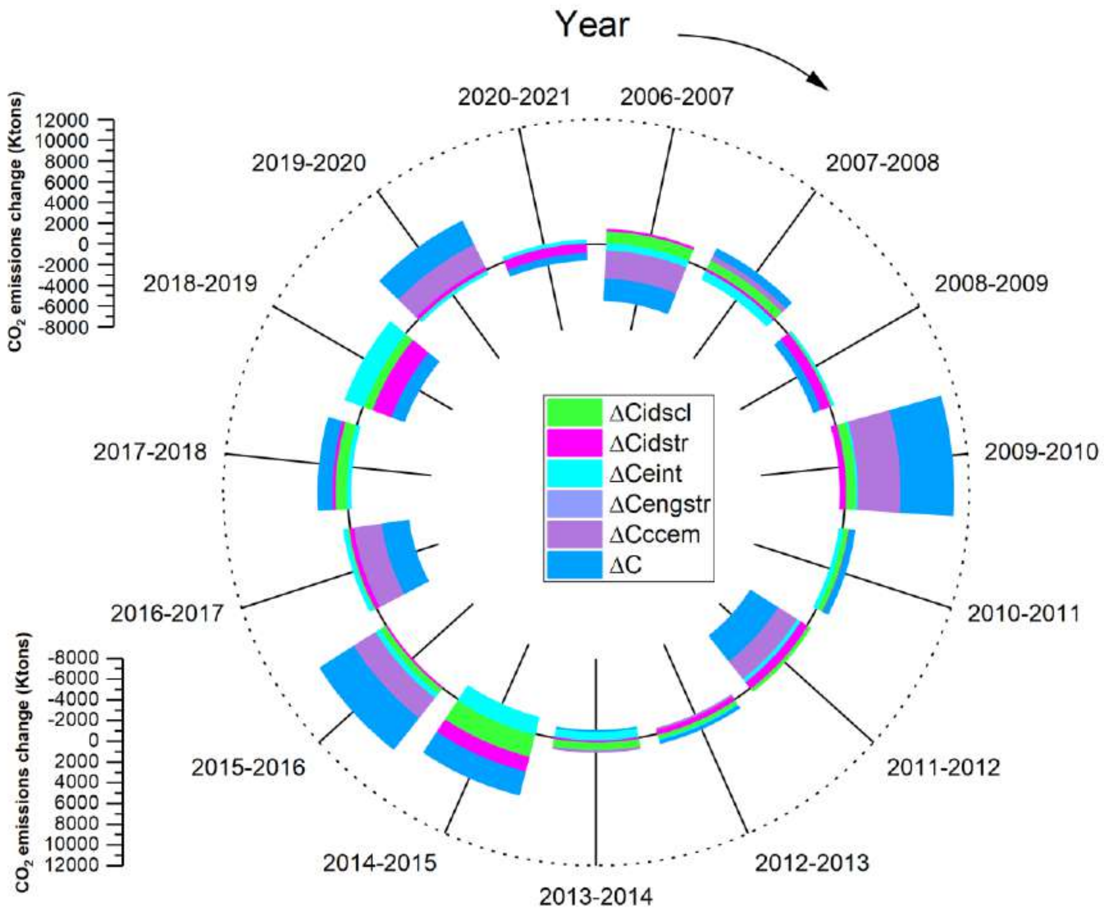

Figure 4.5 Impact of driving forces on Construction materials industry by sub-period.

4.8.1 Industrial scale effect

The effect of change in industrial scale in Algerian non-energy industries resulted in a significant increase in energy-related CO_2 emissions, as depicted in figure 4.3. This factor had the most substantial impact on the change in CO_2 emissions compared to the other influencing factors. Stated differently, the increase in industrial scale requires an equivalent increase in both the quantity of energy required and the corresponding emissions of CO_2 resulting from energy consumption.

During the study period, the changes in industrial scale resulted in a significant increase in energy-related CO_2 emissions. These increases accounted for 194.36%, 119.25%, 101.93%, 109.35%, 306.02, 316.93% and 105.77% of the total energy-related CO_2 emissions in the "construction materials industry" (figure 4.5), the "iron and steel, mechanical, electronic and electric equipment" industry (figure 4.6), the chemistry industry (figure 4.7), the "food products, beverages and tobacco" industry (figure.4.8), "textiles, clothing and leather" industry (figure.4.9), the "construction and public works" industry (figure 4.10), and other industries (figure 4.11), respectively. The CO_2 emissions of the "textiles, clothing, and leather" industry and the "construction and public works" industry experienced a notable increase as a result of the expansion of industrial scale.

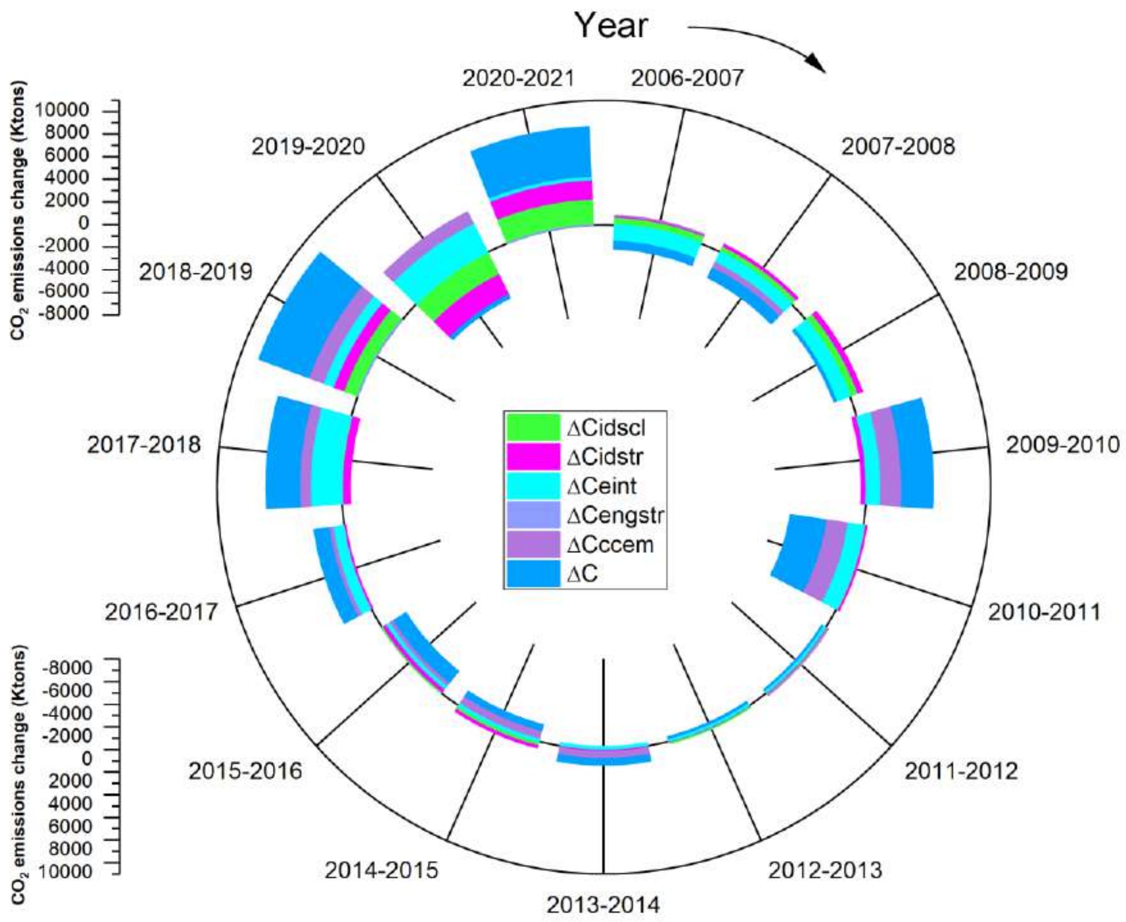

Figure 4.6 Impact of driving forces on "iron & steel, mechanical, electronic & electric equipment" industry by sub-period

The industrial scale has diverse effects on energy-related CO_2 emissions in China's heavy industry [77]. While the study emphasizes that labor productivity raises CO_2 emissions and energy intensity reductions reduce emissions, the influence of industry scale varies between time periods. This shows that the relationship between industrial scale and CO_2 emissions is complex and context-dependent, demanding additional research to fully comprehend its implications for emissions reduction measures.

The scale economy efficiency in China's industry has been found to inhibit the decoupling process of economic growth from CO_2 emissions, suggesting that the scale of industrial activities can hinder improvements in energy and production efficiency [78]. Technological advancements and improvements in energy efficiency are crucial in mitigating the industrial scale effect on CO_2 emissions. The decline in energy intensity has been a significant factor in reducing emissions in China's industrial sector [79-80]. Policy measures focusing on energy conservation and emissions reduction, tailored to the specific characteristics of different regions and industries, can help manage the industrial scale effect. This includes promoting energy-efficient technologies and optimizing industrial structures [11] [80-81].

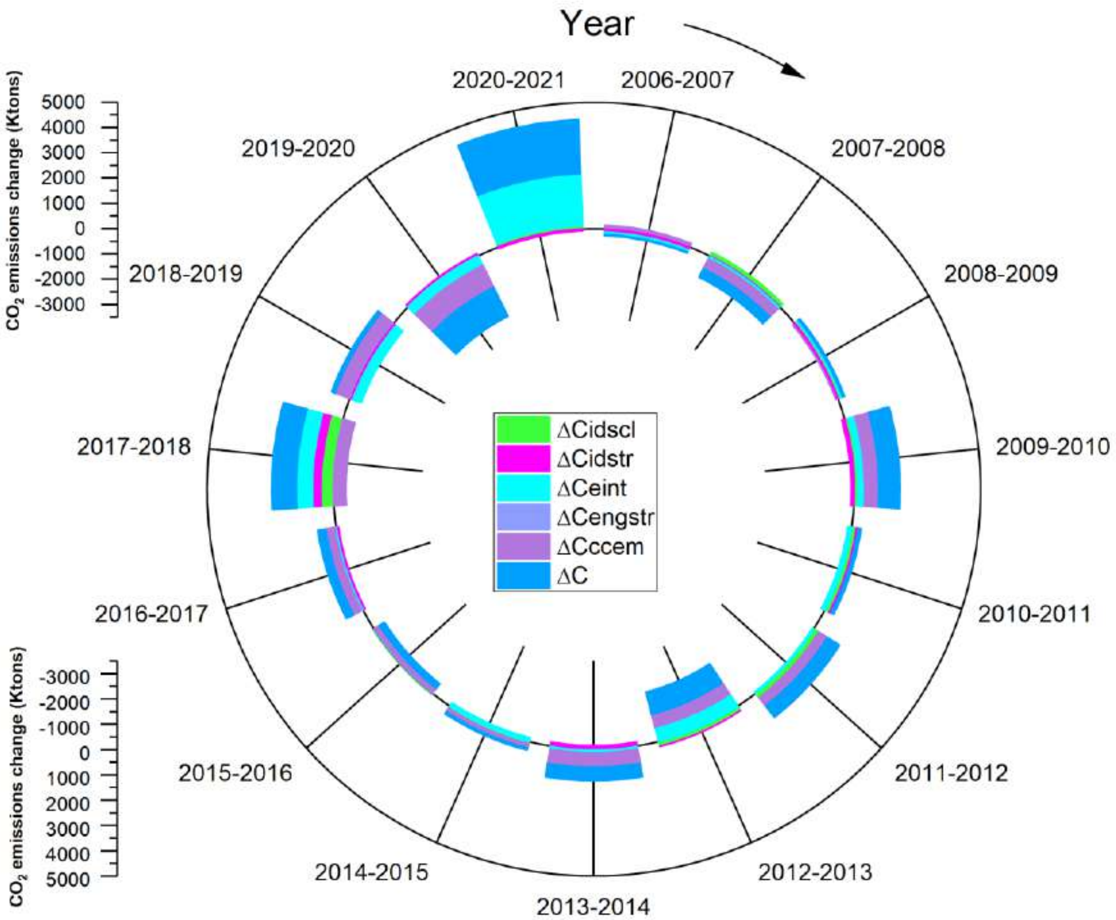

Figure 4.7 Impact of driving forces on chemistry industry by sub-period.

4.8.2 Industrial structure effect

The relationship between industrial structure and energy-related CO_2 emissions varies significantly between developed and developing countries, influenced by factors such as economic development stages, technological advancements, and policy frameworks. In developing countries, industrial structure upgrades often initially increase CO_2 emissions due to industrialization but eventually lead to reductions as economies transition towards more service-oriented and technologically advanced sectors. In contrast, developed countries typically experience a more direct reduction in emissions as they shift from manufacturing to service sectors, supported by advanced technologies and stringent environmental regulations

The value added by each non-energy industry was compared to the total value added by non-energy industries to determine the structure of the industrial sector. Across Algeria's non-energy sectors, different subsectors have a varying share of the industrial value added. In terms of industrial value added, the "construction and public works" sub-sector accounted for 139.24%, followed by the "food, beverage, and tobacco" at 120.85%, the chemistry at 100.20%, the construction materials at 92.24%, the textile, clothing, and leather sub-sector at 73.24%, and the "other industries" at 23.95%. In basic terms, an expansion of the industrial structure is likely to lead to an increase in energy-related carbon dioxide emissions across all non-energy sub-sectors. figure 4.4 and figure 4.9 show that CO_2 emissions increased by 74.89% due to the change in industrial structure, and by 30.28% in the "construction materials" and "construction and public works" sub-sector due to change in energy consumption. The synergy between energy and industrial structures can significantly reduce carbon intensity. This effect is particularly pronounced in regions with abundant energy resources, where environmental regulations and green innovations amplify the reduction in emissions [82]. Within countries, regional variations exist in how industrial structure impacts emissions. For instance, in China, eastern and western regions have consistently reduced emissions through industrial upgrades, while central regions initially saw increases before reductions [83]. In developing countries, the initial stages of industrialization may lead to increased emissions, but with appropriate policies and technological advancements, these countries can achieve significant reductions. Conversely, developed countries benefit from advanced technologies and regulatory frameworks that facilitate a more direct reduction in emissions as they transition to service-oriented economies.

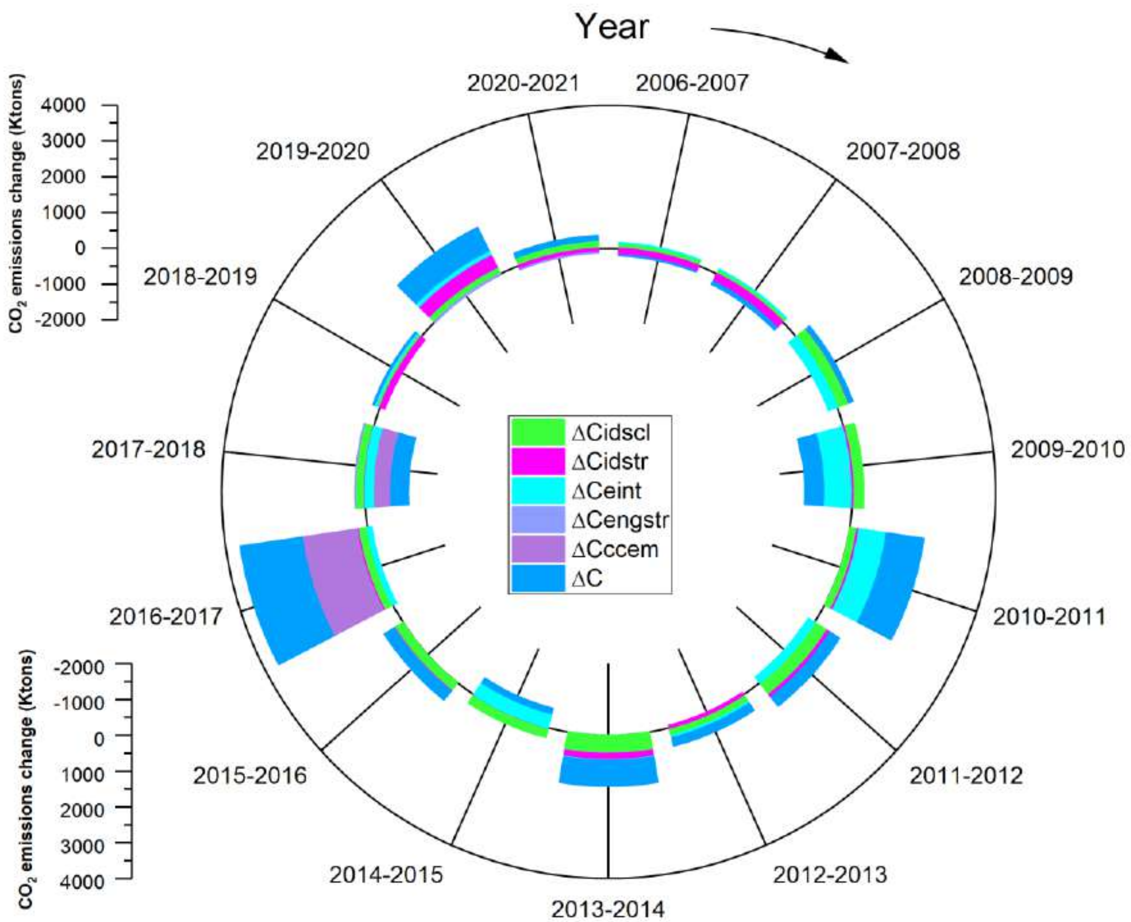

Figure 4.8 Impact of driving forces on "food products, beverages and tobacco" industry by sub-period.

4.8.3 Energy intensity effect

The measurement of energy intensity involved a comparison between the energy utilized in the production procedure and the overall value added by the industrial sector. Reductions in energy intensity result in decreased energy consumption per unit of value added within an individual industry. In the majority of the sub-periods, it was observed that energy intensity had negative effects on the emissions of CO_2. The relationship between energy intensity and economic performance is complex and varies across different sectors and regions. In China, technological advancements and industry-specific policies have contributed to a decline in energy intensity across industries like pulp and paper, cement, and aluminum. Rising energy costs and policies promoting scale economies have been significant factors in reducing energy intensity, thereby enhancing economic performance [80]. European studies indicate that economic expansion is sensitive to energy intensity, particularly in lower-income regions, suggesting that technological innovation and policy interventions are crucial for improving energy efficiency and economic outcomes [84]. The impact of energy intensity on economic performance is not uniform across regions or industries. In China, trade openness and technology development have led to declines in energy intensity in only a few industries, while in Europe, the effects vary depending on the degree of development and time period.

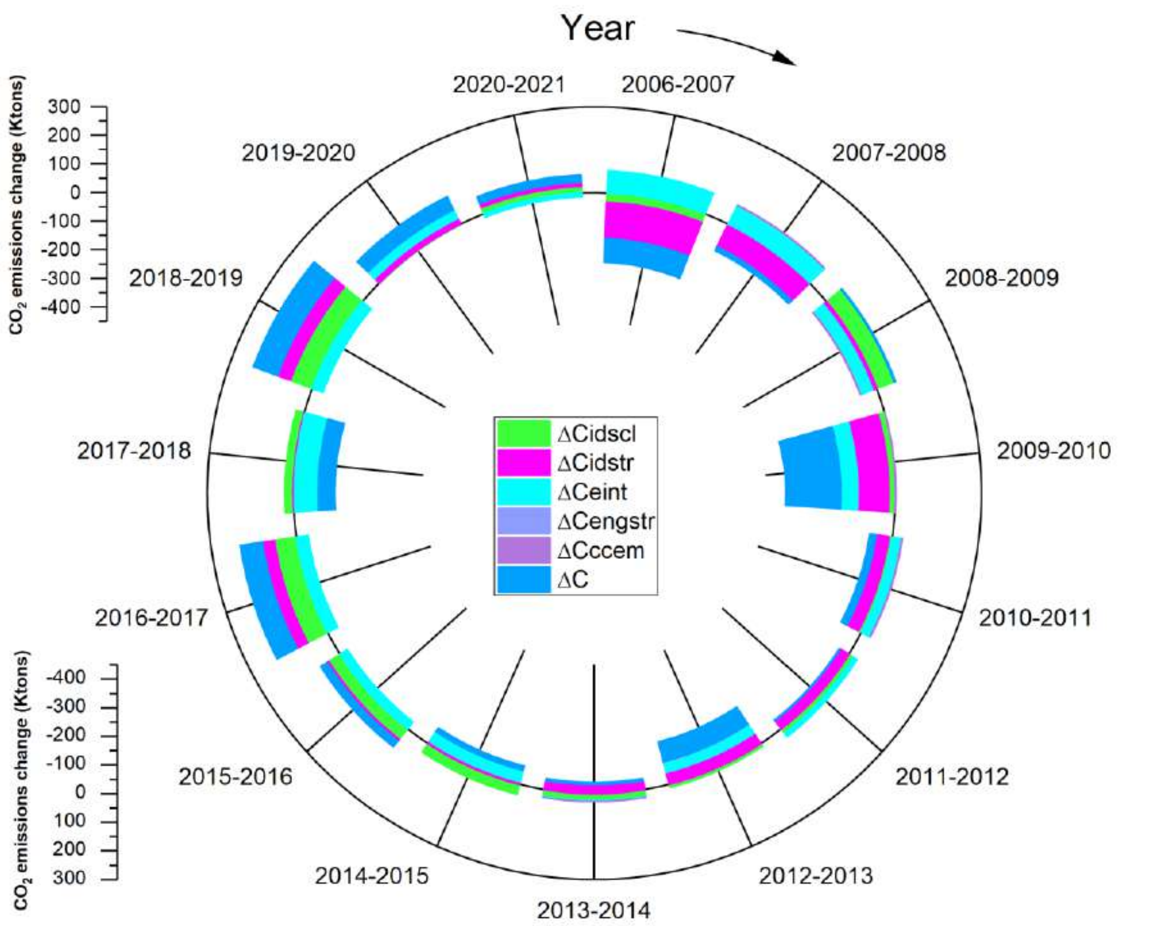

Figure 4.9 Impact of driving forces on "textiles, clothing and leather" industry by sub-period.

4.8.4 Energy structure effect

Energy structures affect greenhouse gas emissions in the sector by determining the ratio of carbon emissions from high-carbon and low-carbon energy sources. The optimization of low-carbon energy structures is more robust than high-carbon energy structures, leading to a decline in carbon emissions from high-carbon sources. Industries with intermediate energy use contribute to carbon emissions, while heavy industries show minimal changes. The change in industrial structure is linked to carbon emissions from energy use [85].

Changes to the energy structure of Algeria's non-energy industries have had little impact on the country's rising CO_2 emissions, an effect that may be linked back to the unique characteristics of these industries. Of the total energy used by the non-energy sector, 51% came from natural gas. Overall, the energy structure effect of non-energy sectors remained relatively stable throughout the duration of the research. Thus, the influence of the energy structure on the emissions of CO_2 related to energy was insignificant.

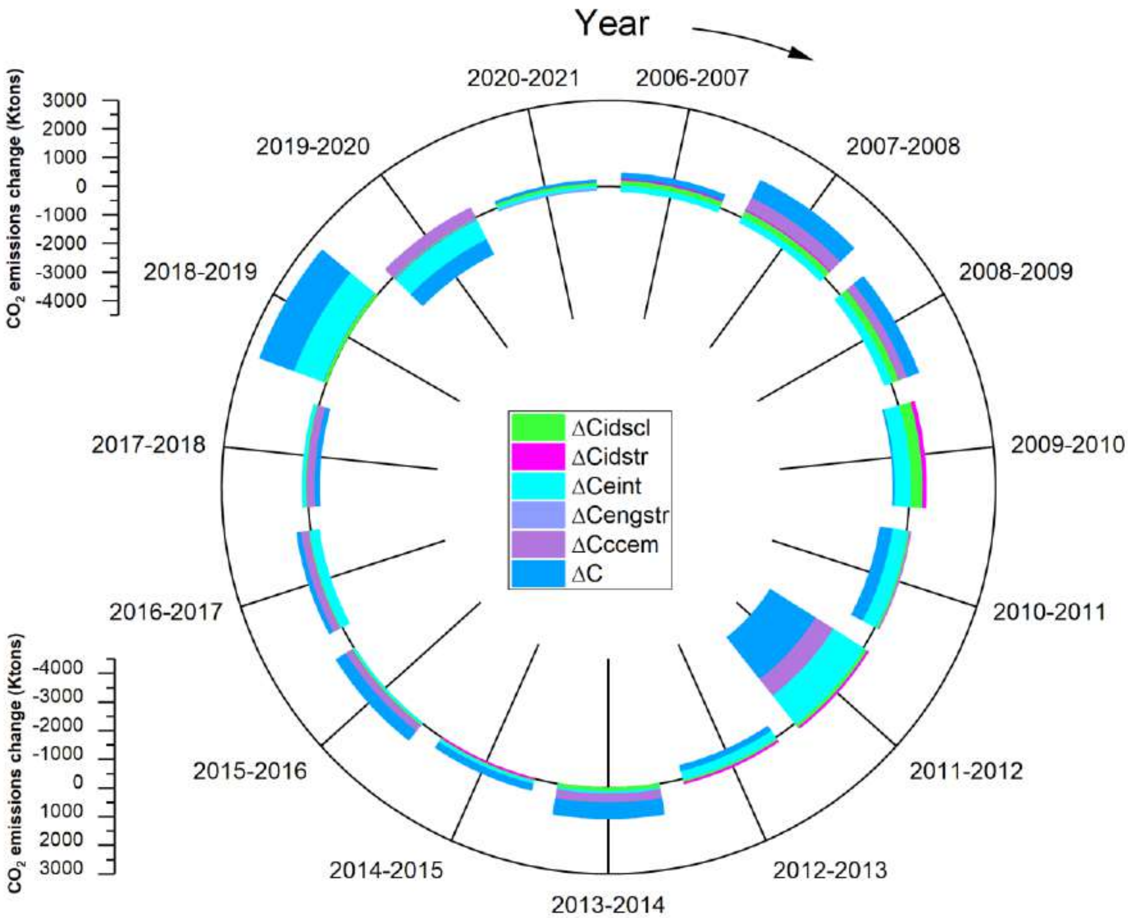

Figure 4.10 Impact of driving forces on "construction and public works" industry by sub-period.

4.8.5 Carbon emission coefficient effect

The alteration in emission coefficient had a net positive effect on CO_2 emissions; The findings of the sub-period analysis indicate that, with the exception of the periods spanning from 2007-2008, 2011-2013, 2015-2016, and 2017-2018, the alterations in the emission coefficient led to an increase in CO_2 emissions across the majority of stages. Energy-related CO_2 emissions changed by 24.25% in the "construction materials" (figure 4.4), 38.7 % in the "iron and steel, mechanical, electronic, and electric equipment" (figure 4.5), 6.7 %in the "chemistry" (figure 4.6), 24.2 % in the "food, beverage, and tobacco" (figure 4.7), 123.2 % in the "construction and public works" (figure 4.9).

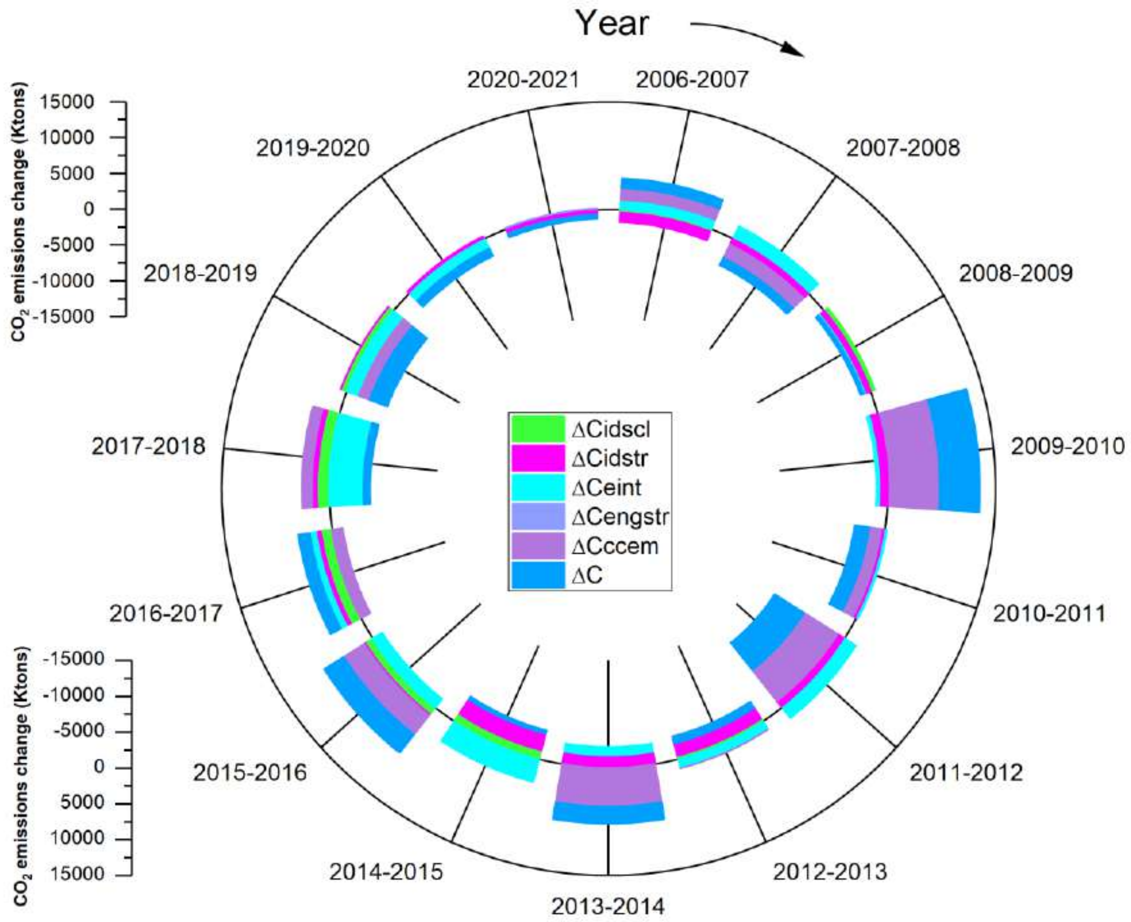

Figure 4.11 Impact of driving forces on "other industries" sub-sector by sub-period.

Non-energy industries can implement several strategies to minimize the effects of carbon emission coefficients on their operations and profitability. These strategies focus on integrating sustainable practices, optimizing production processes, and leveraging policy frameworks to balance environmental and economic goals.

Integrating renewable energy sources such as solar, wind, and hydroelectric power can significantly reduce reliance on fossil fuels, thereby lowering carbon emissions [10-12]. The effective carbon management and policy integration play a crucial role in decarbonization strategies [11]. Implementing carbon control policies can incentivize industries to cut emissions while maintaining profitability [86]. Furthermore, the strategic application of carbon tax policies, combined with approaches like activity-based costing and the theory of constraints, can accelerate decarbonization efforts and strengthen industrial competitiveness [87].

4.9 Mitigation strategies in non-energy industries

Mitigating greenhouse gas emissions in industries is a complex challenge that necessitates a combination of technological, operational, and policy-driven approaches. The most effective measures include increasing energy efficiency, using renewable energy sources, installing carbon capture systems, and encouraging sustainable behaviors in various industries. These methods aim to reduce emissions while also promoting a transition to a low-carbon economy.

4.9.1 Technological Innovations

4.9.1.1 Carbon capture, utilization, and storage (CCUS)

This technology captures carbon dioxide emissions from industrial processes and stores them underground or utilizes them in other processes, preventing their release into the atmosphere. Industries can implement carbon capture and storage (CCS) technologies to significantly reduce greenhouse gas emissions by integrating various capture methods, optimizing storage solutions, and addressing economic and regulatory challenges. CCS technologies are crucial for industries that are hard to decarbonize, such as cement, steel, and petrochemicals, as they allow for the continued use of fossil fuels while mitigating CO_2 emissions. The research by Monteiro and Rossanary [89] analyzes the economic feasibility of including utilization of CO_2 in CCS systems within the cement industry. This includes a reference Carbon Capture and Storage (CCS) chain and three alternative CCUS chains involving the production of ethanol, polyols, or food-grade CO_2. The successful deployment of CCS involves selecting appropriate capture technologies, ensuring efficient storage, and overcoming economic and regulatory barriers [88].

4.9.1.2 Artificial intelligence and machine learning

Artificial Intelligence and Machine Learning technologies are used to predict, monitor, and minimize CO_2 emissions across various industries, optimizing processes to achieve net-zero emissions. Artificial intelligence (AI) is a fundamental driver of the new Industrial Revolution, with the potential to transform innovation efficiency worldwide. Countries around the world are focused on AI development, as seen by policies such as the United States Select Committee on AI, the European Union's Coordinated Plan on Artificial Intelligence, and China's New

Generation of AI Development Plan [89]. Clusters have an important role in regional competitive advantage, particularly in AI innovation. Wang et al. contribute to the subject by giving a comprehensive approach to identify AI clusters, illustrating the positive influence of industry policies on innovation inside these clusters, and suggest network centrality as a critical factor in the context.

4.9.2 Energy Efficiency Improvements

Improving industrial energy efficiency in developing countries is crucial for enhancing economic competitiveness, reducing energy costs, and mitigating environmental impacts. The strategies for achieving these improvements are multifaceted, involving policy frameworks, technological advancements, and market-oriented approaches. These strategies not only address the immediate energy efficiency needs but also contribute to broader sustainable development goals.

4.9.3 Renewable Energy Adoption

4.9.3.1 Transition to Renewable Energy

Industries are increasingly investing in solar, wind, and bioenergy projects to reduce their carbon footprint and reliance on fossil fuels. The transition to renewable energy in the manufacturing industry could see renewable sources meet up to 21% of final energy demand and feedstock use by 2050, a significant increase from current levels [86-89]. Bioenergy and biofeedstocks are projected to account for three-quarters of this renewable use, with solar heating and heat pumps making up the remainder. However, achieving this potential requires addressing economic competitiveness, local biomass availability, and developing supportive policies to encourage private sector investment [90].

4.9.3.2 Carbon Neutral Fuels

The use of renewable energy and synthetic fuels can significantly reduce emissions by replacing fossil fuels in industrial processes [91]. The integration of renewable energy and synthetic fuels in industry represents a promising pathway towards achieving carbon neutrality and reducing reliance on fossil fuels. Synthetic fuels, produced using renewable energy sources and captured CO_2, offer a carbon-neutral alternative that can be seamlessly integrated into existing infrastructure, thus facilitating a smoother transition for industries. These fuels are particularly valuable in sectors where electrification is challenging, such as high-heat industrial processes and transportation. The potential for synthetic fuels to contribute to a sustainable energy future is significant, but it requires overcoming economic, technological, and regulatory challenges. Synthetic fuels can replace fossil fuels in industrial applications, contributing to significant reductions in CO_2 emissions. For instance, in Germany, a model predicts an 88% decrease in industrial CO_2 emissions by 2050 through the use of synthetic fuels, aligning with national climate goals [92]. The "drop-in" nature of synthetic fuels allows them to be used with existing infrastructure, reducing the need for extensive modifications [93]. he production of synthetic fuels is currently expensive, but advancements in technology and decreasing costs of renewable energy are improving their economic viability [93-94]. Renewable syngas, a type of synthetic fuel, can become cost-competitive with fossil-based syngas under certain conditions, such as high natural gas prices and increased carbon taxes [94]. The development of advanced catalysts and integration of renewable energy sources are critical for enhancing the efficiency and scalability of synthetic fuel production [95].

4.9.4 Policy and economic measures

4.9.4.1 Carbon pricing and incentives

Carbon pricing regimes, such as carbon taxes and emissions trading systems (ETS), are pivotal in incentivizing industries to reduce greenhouse gas emissions. These mechanisms internalize the cost of carbon emissions, encouraging industries to adopt cleaner technologies and practices. The effectiveness of these incentives is influenced by several factors, including the design of the pricing mechanism, complementary policies, and the economic context of the region. Implementing carbon taxes and cap-and-trade programs internalizes the social cost of carbon, encouraging industries to adopt greener practices [96]. Carbon pricing makes carbon emissions financially burdensome, prompting industries to seek cost-effective emission reduction strategies. This internalization of external costs encourages industries to innovate and invest in low-carbon technologies [97-98]. Participation in carbon markets can enhance a company's market access and competitiveness by improving its green brand image and compliance with environmental regulations [99]. The way carbon revenues are utilized can significantly impact emission reductions. For instance, returning revenues to households can offset higher fuel prices, maintaining public support for carbon pricing policies [100]. Carbon pricing incentivizes industries to adopt clean technologies such as carbon capture and storage (CCS), electrification, and sustainable manufacturing processes. This is crucial for decarbonizing production processes and reducing emissions [96]. The carbon market stimulates innovation by providing economic incentives for developing new technologies that reduce emissions. This is particularly effective in technology-intensive and high-polluting industries

[99] [101]. The success of carbon pricing is bolstered by international cooperation and coordination. Harmonizing carbon pricing mechanisms across borders can prevent emissions leakage and enhance the overall effectiveness of global mitigation efforts [102-103]. The effectiveness of carbon pricing varies based on local economic conditions and market structures.

4.9.4.2 Voluntary programs and agreements

These initiatives support industries in transitioning to low-carbon technologies and practices, often proving more effective than mandatory regulations [104]. Voluntary programs and agreements have emerged as significant tools in promoting industry compliance with environmental regulations. These initiatives offer a flexible and cost-effective alternative to traditional command-and-control regulations, aiming to enhance corporate environmental performance. However, their effectiveness is contingent upon several key factors that influence their success. These factors include the design and structure of the programs, the presence of regulatory threats, the role of government supervision, and the motivations of participating firms. Understanding these elements is crucial for assessing the potential of voluntary programs to achieve environmental goals. The effectiveness of voluntary programs often depends on the backdrop of regulatory threats. Programs are more successful when there is a credible threat of future regulation, which motivates firms to participate proactively [105-106]. The Dutch covenants demonstrate the potential of negotiated agreements to achieve high compliance and environmental performance, particularly when supported by strong industry representation and ambitious goals [107].

4.9.5 Sustainable practices and community engagement

Expanding public transportation systems and promoting electric vehicles can reduce emissions from the transportation sector, which is closely linked to industrial activities [96][108]. Reducing emissions from the transportation sector, which is closely linked to industrial activities, is a multifaceted challenge that requires a combination of technological, policy, and behavioral changes. The transportation sector is a significant contributor to global CO_2 emissions, accounting for a substantial portion of emissions from energy and industry. Strategies to mitigate these emissions focus on electrification, renewable energy adoption, and efficiency improvements, among others. These strategies are crucial for achieving carbon neutrality and meeting international climate targets. Despite technological advancements, the growth in industrial scale can offset efficiency gains. Therefore, addressing the scale of industrial activities and transportation demand is crucial [109]. The transportation sector is intricately linked with other industrial sectors, and emissions are influenced by both intra- and extra-industry factors. A comprehensive approach that considers these linkages is necessary for effective emission reduction [103] [110]. The transport sector's carbon emission linkages indicate that upstream interventions in the supply chain can have significant impacts on reducing emissions [110].

Collaboration among governments, businesses, and civil society is crucial for implementing effective mitigation strategies and fostering a sustainable future [108]. Community-based strategies for reducing greenhouse gas emissions in the industry are increasingly recognized as effective due to their ability to engage local populations and tailor solutions to specific community needs. These strategies often involve a combination of technological, behavioral, and policy interventions that leverage local resources and knowledge. The effectiveness of these strategies is enhanced when they are integrated into broader frameworks that include government and industry collaboration. Engaging citizens in energy-saving activities is a cost-effective strategy for reducing emissions. Community-based initiatives (CBI) that focus on renewable energy generation, such as solar and wind, have shown significant potential in reducing greenhouse gas emissions. These initiatives can reduce the carbon footprint of beneficiaries by up to 24% compared to business-as-usual scenarios [111]. Furthermore, an effective collaboration between stakeholders, including local communities, governments, and industries, is essential [112].

4.10 Conclusion

The non-energy industry sector accounts for a substantial share of Algeria's energy consumption and CO_2 emissions, making it a critical area for projecting future emission trends and identifying reduction opportunities. The evolution of its energy demand reflects the sector's growing contribution to the country's economic development. The results provide essential insights that underscore the strategic importance of this sector and support its effective management. While these strategies offer significant potential for reducing greenhouse gas emissions, challenges remain in their implementation. Economic considerations, technological limitations, and the need for policy reforms can hinder progress. Additionally, the transition to a low-carbon economy requires substantial investment and innovation to balance development needs with environmental sustainability. Therefore, ongoing research and collaboration are essential to overcome these barriers and achieve meaningful climate change mitigation. The findings are promising and suggest that the non-energy industry can develop a variety of emission reduction strategies, including plant conversion and alternative mitigation scenarios.

Chapter 05

CO_2 emissions Conversion to Methanol strategy: Addressing Non-Energy Industrial Emissions in Algeria

5.1 Introduction

The industrial sector is a significant contributor to CO_2 emissions, driven by various factors that can be mitigated through targeted strategies. Key factors influencing CO_2 emissions in the industrial sector include economic output, energy intensity, industrial structure, and energy sources. Mitigation strategies focus on improving energy efficiency, optimizing industrial structures, and transitioning to low-carbon energy sources. These factors and strategies are crucial for reducing the carbon footprint of the industrial sector. The objective of this chapter is modeling and forecasting of CO_2 conversion to methanol scenario to reduce the impact of CO_2 emissions of Algeria's non-energy industries.

5.2 Algeria's sources of CO_2 emissions

The primary Algeria's sources of CO_2 emissions include the energy sector, non-energy industrial processes, transport, and household activities. These sectors contribute significantly to the accumulation of greenhouse gases in the atmosphere, which in turn drives climate change by increasing global temperatures, altering weather patterns, and causing sea levels to rise. The energy sector, particularly through the combustion of fossil fuels, is the largest contributor to CO_2 emissions, accounting for a substantial portion of global emissions.

Table 5.1 Algeria's Sectoral Contribution to CO_2 Emissions.

Sector	**Key Emission Sources**	**Citation**
Non-energy Industry	Cement production, iron and steel, and chemical production	[10-12] [63]
Household	Combustion of natural gas, coal, and LPG for heating and cooking	[113-115]
Transport	Combustion of gasoline and diesel in vehicles	[12] [116-117] [119]
Energy	Combustion of coal, oil, and natural gas for electricity and heat production	[4] [118] [120-123]

Non-energy industrial processes such as construction material production, iron and steel, and petrochemical activities also play a significant role. The transport sector, driven using gasoline and diesel, further exacerbates the situation. These emissions have profound impacts on climate change, necessitating urgent mitigation strategies. The sectoral contribution of CO_2 emissions varies by region and country, but the energy, transport, and non-energy industrial sectors are consistently among the largest contributors (Table 5.1).

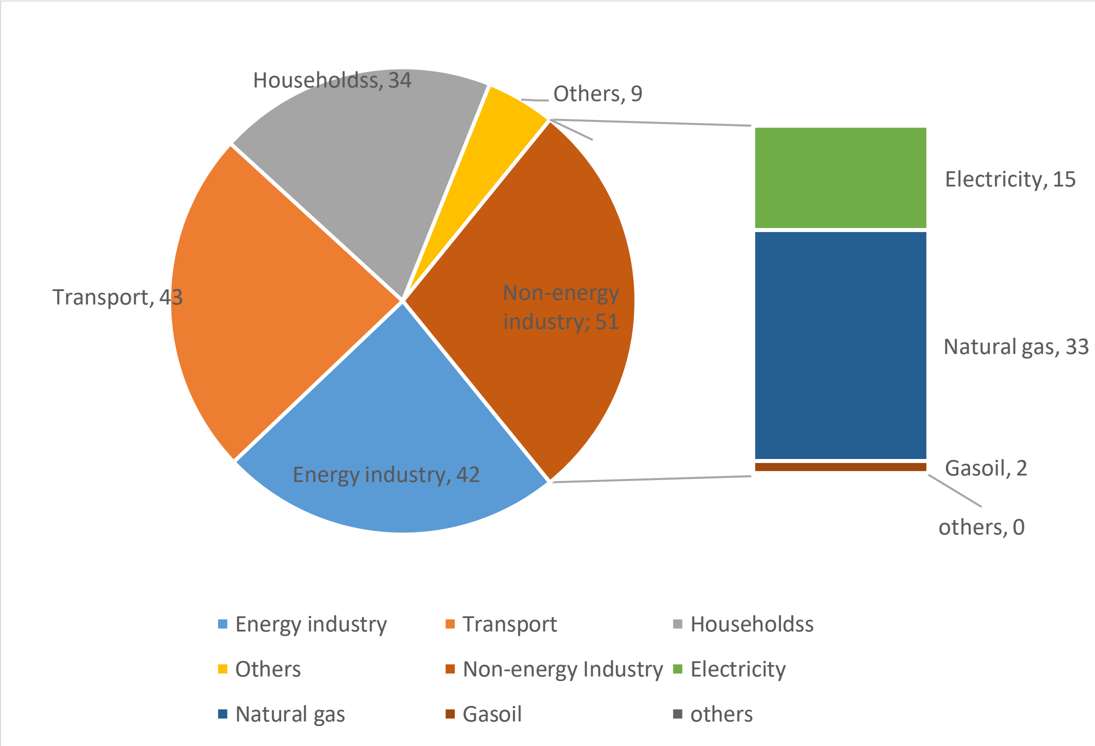

Figure 5.1 Distribution of CO_2 emissions (Mt), 2021.

Figure 5.1 depicts the distribution of CO2 emissions across different sectors. The non-energy industry sector stands out as the predominant contributor, representing 51 Mt of emissions, with the energy industry following closely at 42 Mt. Transport accounts for 43 Mt, while the household sector makes up 34 Mt. Regarding CO2 emissions categorized by fuel type, it is evident that natural gas dominates as the leading contributor, accounting for 33 Mt of total emissions. Electricity generation represents 15 Mt, whereas gasoil contributes 2 Mt.

5.2.1 Analysis of CO_2 emissions in the energy sector

The energy sector is the largest source of greenhouse gas emissions, primarily due to the combustion of fossil fuels such as coal, oil, and natural. According to recent data, CO_2 emissions from the energy sector have shown a mixed trend over the past few decades

[03]. While some regions have experienced a decline in emissions due to the adoption of renewable energy sources and energy efficiency measures, others continue to see rising emissions driven by increasing energy demand and reliance on fossil fuels [20], [60], [65], [84]. China is the largest contributor to global CO_2 emissions, accounting for a significant portion of emissions from the energy sector [67]. The United States is another major contributor to energy-related CO_2 emissions. However, recent data shows a decline in emissions from the US power sector, driven by the transition from coal to natural gas and the growth of renewable energy [124]. European countries such as the United Kingdom and Germany have made significant progress in reducing CO_2 emissions from the energy sector, primarily through the adoption of renewable energy and energy efficiency measures [125-126].

Many developing countries, particularly those with rapidly growing economies, are experiencing increasing CO_2 emissions from the energy sector. Algeria's energy sector is predominantly dependent on fossil fuels, specifically oil and natural gas. This dependency significantly contributes to CO_2 emissions, as the usage of fossil fuel energy directly increases emissions [127].

Figure 5.2 depicts the pattern of CO_2 emissions in the energy sector from 2000 to 2021. During the initial decade of the period, from 2000 to 2010, the darkened region signifying very low emissions ranging from 15.84 to 25 Mt. This constancy indicates that energy demand and sectoral efficiency had few variations throughout that decade. Beginning in 2011, the radius of the curve initiates a more noticeable increase. Emissions gradually transition into the 28–42 Mt range, indicating heightened sector activity or an increase in carbon-intensive energy consumption. This economic advancement remains gradually throughout the mid-2010s, indicating an annual increase in CO_2 emissions. The most significant increase is evident post-2018. In 2021, emissions exceeded 42 Mt, representing the peak amount for the entire time. The chart illustrates sustained rising pattern, increasing from 15 Mt to over 42 Mt. This pattern emphasizes the increasing environmental challenges related to the energy industry and focuses on the importance for implementing more effective mitigation and efficiency-enhancing strategies.

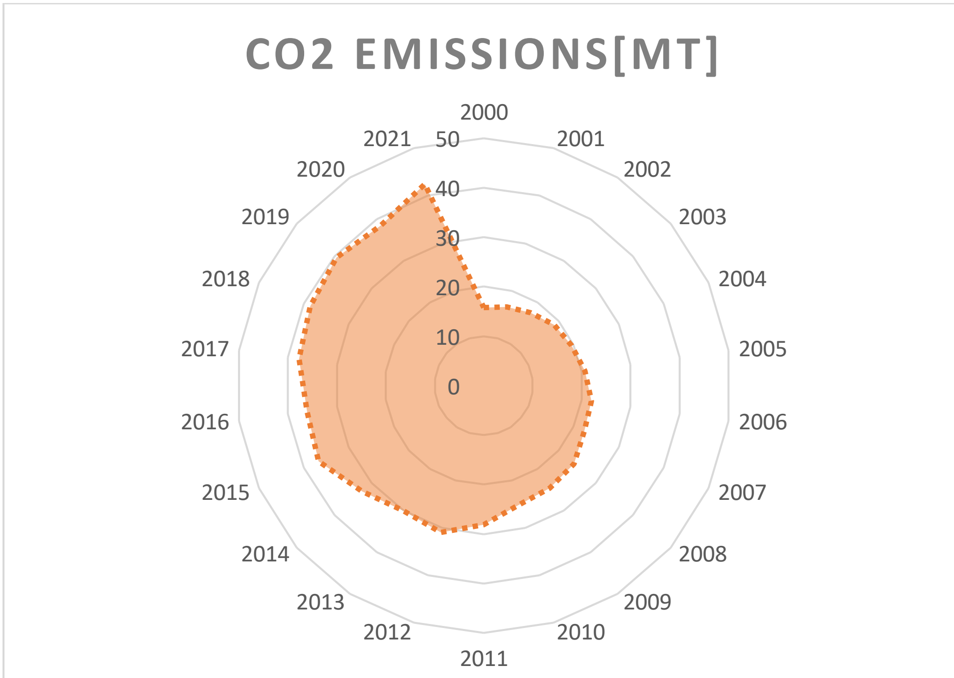

Figure 5.2 CO_2 emissions in the Energy sector.

Despite the potential of renewable energy and technical innovation to mitigate CO_2 emissions, its effectiveness in Algeria has been constrained. Positive developments in renewable energy and technological innovation can reduce emissions; however, the cumulative impact has been insufficient to balance emissions from fossil fuels [128].

5.2.2 Analysis of CO_2 emissions in the non-energy industrial sector

The primary drivers of CO_2 emissions in Algeria's industry sector are multifaceted, involving economic activity, industrial scale, energy consumption, and the energy mix. The industrial sector, particularly non-energy industries such as construction materials, iron and steel, and food products, plays a significant role in the country's carbon emissions. The increase in CO_2 emissions is primarily driven by the expansion of industrial activities and the reliance on fossil fuels, despite efforts to improve energy efficiency and incorporate renewable energy sources. The following sections detail the key drivers of CO_2 emissions in Algeria's industry sector. Economic activity is a major driver of CO_2 emissions in Algeria, with industrial scale contributing significantly to the increase in emissions. The industrial scale effect alone contributed 26.12 million tons of CO_2 emissions from 2006 to 2021[11]. The expansion of industrial activities, particularly in the construction materials industry, has been identified as a significant contributor to the rise in energy consumption and CO_2 emissions [12]. The increase in energy consumption, particularly in non-energy industries, is a key factor driving CO_2 emissions. The activity effect, which reflects the growth in industrial output, has led to a substantial rise in energy use. Despite improvements in energy efficiency, the overall energy intensity in Algeria's industrial sector remains high, contributing to increased emissions. The energy intensity factor has not significantly helped in reducing CO_2 emissions [72]. Algeria's energy mix, heavily reliant on fossil fuels, is a critical driver of CO_2 emissions. Positive shocks in fossil fuel energy led to increased emissions, highlighting the need for a transition to cleaner energy sources [127]. The energy mix factor has contributed to a slight increase in emissions, indicating that the current energy policies have not effectively reduced the reliance on fossil fuels [72]. The industrial structure effect has played a role in reducing emissions, as shifts towards less carbon-intensive industries have been observed. However, the impact is not sufficient to offset the overall increase in emissions [11]. Technological innovation has the potential to reduce CO_2 emissions, with positive changes in technology leading to decreased emissions. However, negative shocks can exacerbate emissions, underscoring the importance of consistent technological advancements [127].

5.2.3 Analysis of CO_2 emissions in the transport sector

Algeria's transport sector is a significant contributor to the CO_2 emissions, primarily due to its reliance on fossil fuels and the increasing demand for mobility driven by urbanization. The transport sector's emissions are influenced by various factors, including the type and age of vehicles, fuel consumption, and urban planning. Rapid urbanization in Algeria has increased the demand for transportation, leading to higher CO_2 emissions [128-129]. The expansion of urban areas necessitates greater mobility, which in turn increases the reliance on road transport. The spatial distribution of emissions is influenced by urban planning, with peripheral areas experiencing higher emissions due to increased travel distances. Urban growth in cities with high population density has resulted in increased vehicle use, intensifying traffic congestion and emissions from fossil fuel-powered vehicles. Algeria has initiated efforts to reduce transport-related emissions by adopting sustainable transport policies, such as the introduction of tramways in cities like Constantine, Algiers and Oran. However, the implementation of renewable energy and energy efficiency programs has not yet achieved significant reductions in CO_2 emissions, indicating a need for more stringent policies and measures [72].

The transport sector remains a second major source of CO_2 emissions in Algeria, efforts to mitigate these emissions face challenges such as urban sprawl, reliance on fossil fuels, and the slow adoption of renewable energy solutions. The transition to sustainable transport systems, including the use of alternative fuels like methanol produced from CO_2, presents a potential pathway to reducing emissions. However, achieving significant reductions will require comprehensive policy implementation and a shift in energy consumption patterns.

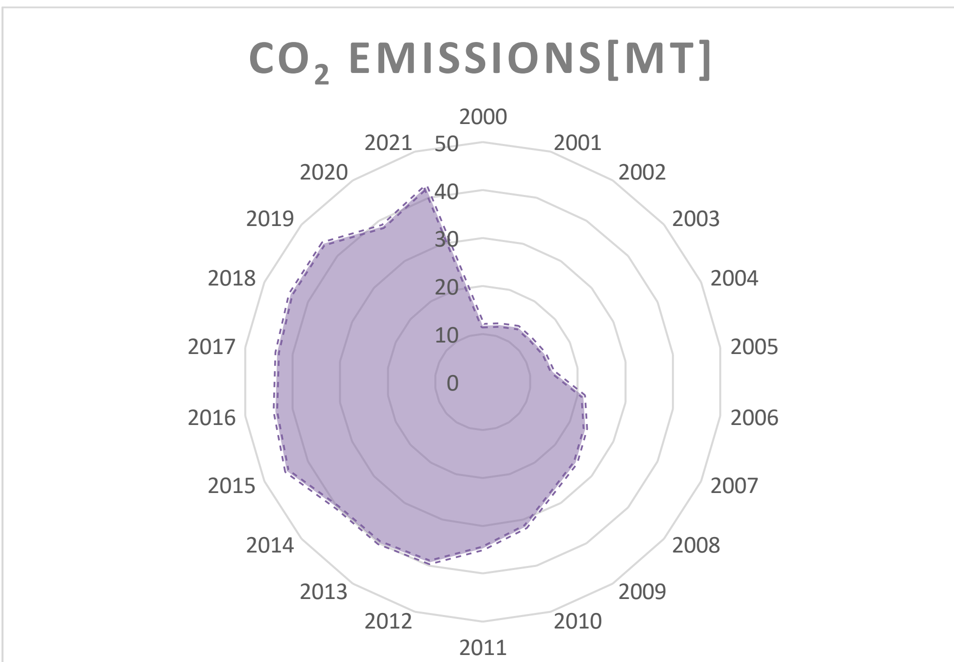

Figure 5.3 CO_2 emissions in the Transport sector.

Figure 5.3 shows the trend of CO_2 emissions from Algeria's transport industry between 2006 and 2021. The graph illustrates a varied although predominantly concerning trend, with emissions varying from a low of 12 Mt to a high of 45 Mt. The average emissions are 36.59 Mt, slightly lower compared to those of the non-energy industrial sector, although demonstrate greater volatility, evidenced by a larger standard deviation of 8.17. The significant negative skewness of -0.81 evident in the chart's distribution signifies a clustering of data points at the upper end of the emission scale, proving the sector's continued substantial influence. This visual data highlights the sector's position as a significant and consistent source of emissions, driven by rising transport demand, dependence on gasoline and diesel, and urban expansion. The figure indicates that initiatives like as urban tramways have been inadequate in changing the basic trajectory, requiring stronger policies, including rapid transition to alternative fuels like methanol.

5.2.4 Analysis of CO_2 emissions in the household and others sector

Algeria's household sector is a major energy consumer, accounting for a large share of the national energy use and significantly affecting greenhouse gas emissions. This sector's energy consumption is influenced by a variety of factors, including urbanization, economic expansion, and the use of traditional energy sources [129]. The primary energy sources for the household sector include natural gas and electricity, both of which are heavily reliant on fossil fuels. Natural gas consumption is particularly high, ranking second in the structure of final energy consumption in Algeria [9]. The energy mix in Algeria has not significantly shifted towards renewable sources, which means that the households sector continues to depend on fossil fuels, contributing to CO_2 emissions [72]. Rapid urbanization and economic growth in Algeria have led to increased household energy consumption. This trend is expected to continue, exacerbating CO_2 emissions unless mitigated by policy interventions. The relationship between income growth and households CO_2 emissions suggests that as income per capita increases, so does energy consumption, further driving emissions [130].

The household sector accounts for 34% of Algeria's CO_2 emissions. Figure 5.4 illustrates this significant contribution, indicating a trend up that corresponds to the factors driving rapid urbanization and economic expansion. The principal energy sources for this sector are natural gas and electricity, both significantly dependent on the fossil-fuel-centric national system.

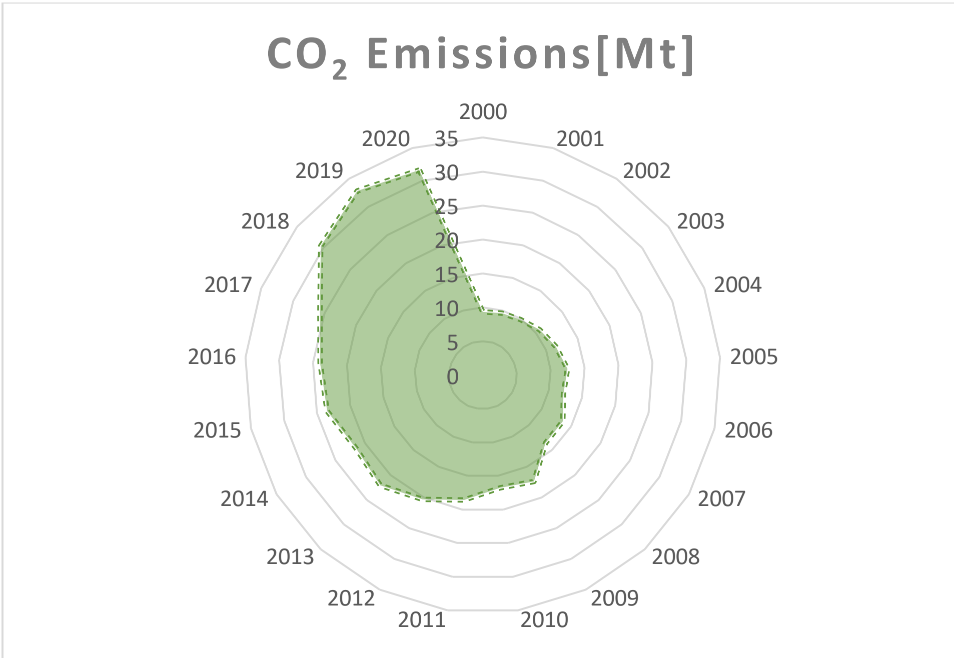

Figure 5.4 CO_2 emissions in the Household sector

The increasing trend of the curve in figure 5.4 depicts an increase of energy consumption associated with rising incomes and urban development. The result suggests current energy mix and efficiency initiatives have not sufficiently separated residential energy consumption from carbon emissions. The introduction of energy-efficient technologies and the integration of renewable energy sources into the household sector could significantly reduce emissions, but this requires stringent policy enforcement and public awareness. The current reliance on fossil fuels and the slow adoption of renewable energy sources highlights the need for a more aggressive approach to energy policy and efficiency measures. Addressing these issues could help Algeria reduce its household sector's carbon footprint and contribute to global efforts to combat climate change.

5.3 Scenarios of CO_2 emissions mitigation in industrial sector

Mitigating CO_2 emissions in the industrial sector is critical for addressing climate change, and several strategies have been identified to achieve this goal. One prominent approach is the implementation of CO_2 capture and storage technologies, which aim to capture emissions from large point sources and store them, thereby directly reducing atmospheric CO_2 levels [77]. Additionally, the adoption of energy-efficient technologies plays a significant role in enhancing industrial energy efficiency, which is essential since industry accounts for approximately 37% of global greenhouse gas emissions, primarily from energy use [78]. The US Climate Change Action Plan emphasizes the importance of both energy-efficient and pollution-preventing technologies to stimulate reductions in CO_2 emissions [79]. Furthermore, recycling carbon through innovative processes can significantly mitigate emissions by reusing CO_2 in industrial applications, thus decreasing reliance on new carbon sources [80]. Enhanced fixation into aquatic biomass is another promising method, as it utilizes CO_2 to promote biomass growth, which can replace fossil carbon in the production of chemicals and fuels, further contributing to emission reductions. Collectively, these strategies highlight the multifaceted approach required to effectively mitigate CO2 emissions in industry, combining technological advancements with policy initiatives to foster a sustainable industrial future. The integration of these methods not only addresses emissions but also promotes energy efficiency and resource conservation, paving the way for a more sustainable industrial landscape [78, 79].

5.4 CO_2 conversion to methanol scenario

5.4.1 Technical potential of Converting Industrial CO_2 to Methanol

The technological development of methanol production methods has transitioned from traditional fossil-based syngas processes to advanced carbon capture and utilization (CCU) approaches that incorporate renewable hydrogen and CO_2 [131-132]. This transition holds considerable importance, due to industrial sectors account for around 20% of global CO_2 emissions. The demand for methanol is expected to rise significantly as a clean energy carrier and chemical precursor [133]. The conversion of industrial CO_2 emissions into methanol presents an effective plan to reduce greenhouse gas emissions and provide a valuable chemical feedstock. The synthesis of methanol from CO_2 can be achieved through a variety of processes, each presenting numerous technical and economic considerations. The viability of these processes is based upon various factors, including conversion efficiency, production costs, and environmental implications.

5.4.1.1 Catalytic processes

In 2019, [8] presented an approach where cobalt oxide precursors were synthesized via reverse microemulsion method and were then calcined in air. After various configurations, the main phase of the CO_3O_4 oxide was formed. It was shown that carbon carbide (CO_2C) could be formed in a low-oxygen environment from cobalt oxide under passive carburization. Thus, CO production via dry-air reforming of methane (DRM) reaction with the use of CO_2C catalysts was demonstrated. The migration of carbon to bulk played a pivotal role in CO_2C formation and deactivation, in which collaboration between the gas-phase and the active phase was highlighted. In addition, it was shown that CO/Al_2O_3 and CO_2C, prepared with different cobalt species and calcination temperatures, both performed for DRM at above 700 °C. Differences in the phase of cobalt led to different catalytic performance. Therefore, there exist unresolved workload and questions for further work on carbons in Co-based catalysts for DRM, including the origin of carbon, in-situ characterization methods, and cyclic stability of carbon consumption [134].

Due to the depletion of fossil energy resources and the growing worldwide need for energy, the rapid utilization of renewable energy in chemical processes has attracted widespread attention. Herein, industrial scale reductions of mid- to high-content ethylene, propylene, aromatics, and their derivatives required in chemical domains have been reviewed by a series of polymerization-based multistage sustainable catalytic cascades (ISMSCC). Such novel processes, fluid catalytic cracking, dewaxing, isomerization and alkylation reactions, were performed to convert ethanol or propanol-derived olefin, carbon monoxide, or aromatic feedstocks directly to alkenes, and further transformed to aromatics with great economic viability. Design strategies and approaches of related operative flow sheets to maximize on-purpose yields were proposed along with techno-economic evaluations. Endowing new functionalities to conventional exothermic methods, indirect-exothermic adiabatic FFOs, were designed and intensified to improve thermal separation efficiency in both daytime or polygeneration hydrogen-fuel and propylene processes. In addition, improvements or new-reaction paths that were overlooked before are reconsidered and discussed throughout the review.

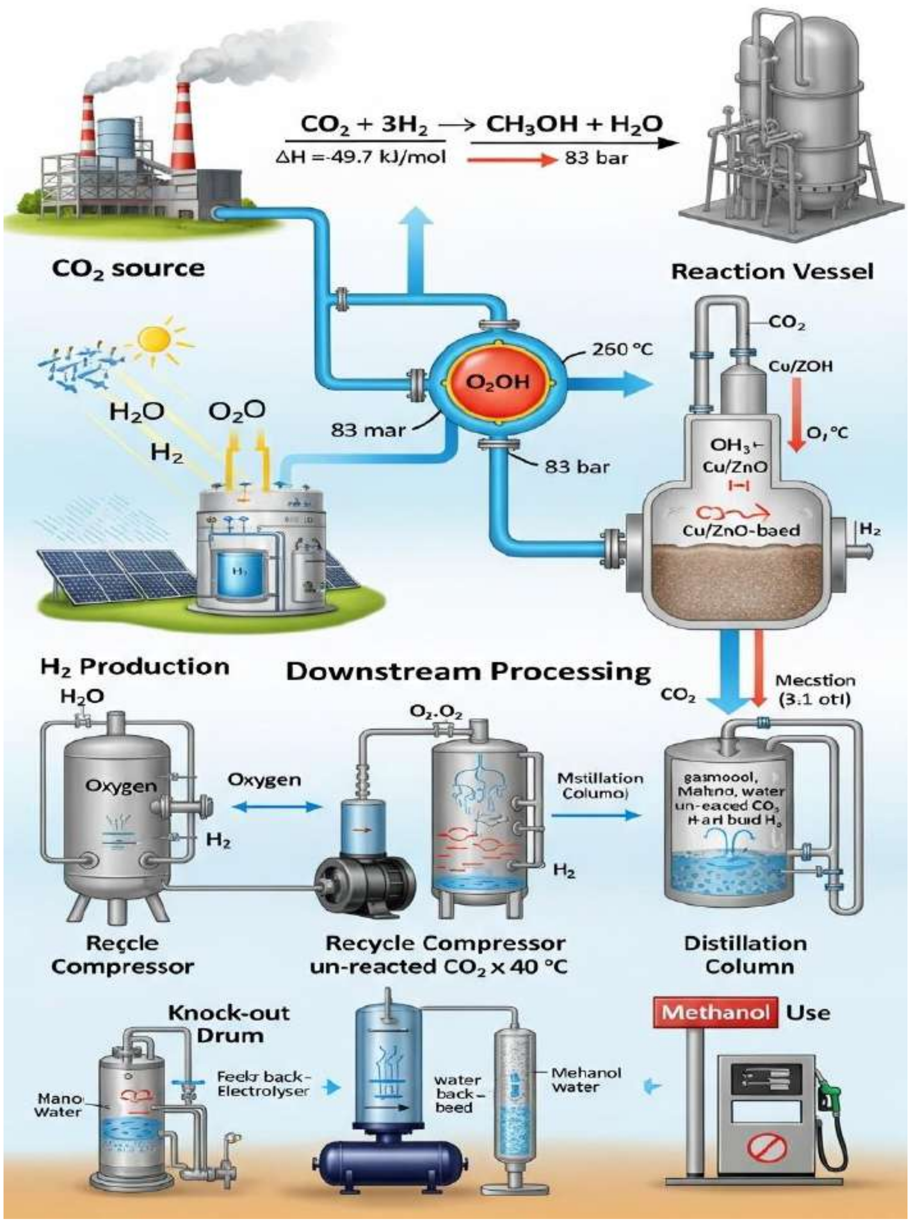

Figure 5.5 CO_2 recycling to methanol

5.4.1.2 Electrochemical methods

The electrochemical reduction of CO_2 to methanol (ECRCM) has become an alluring research field of considerable interest since it would ultimately provide a sustainable and efficient route to store and utilize excess renewable energy from wind or solar [135]. For this transformation the extreme selectivity of copper, which can catalytically convert CO_2 to methanol via an unprecedented 8-electron transfer, should be exploited and improved, to fulfil the technological requirements. The economic viability of this conversion hinges upon two pillars: one of them is the choice of a feasible reactor configuration, and the other is the potential of Cu-electrocatalysts. Paradigmatic reactor configurations have been developed in the form of a 2-compartment single cell, relying on mass transport enhancement of gas-phase CO_2 to the catalytic interface, and the use of electrolytic membranes in absence of porous electrode materials.

5.4.2 Environmental impact and sustainability of methanol recycling

Methanol is a clean, sustainable energy source which can be produced using conservative energy sources such as natural gas via the steam reforming process or from more innovative and environmentally friendly technologies such as the gasification of heavy residue or biomass [1]. The conversion of methanol into others fuels such as gasoline is then required. A more recent promising technology for methanol production from CO_2 as carbon feedstock is also currently under development. This would greatly contribute to a paradigm shift in the CO_2 zero balance by aborting it and turning it into useful chemical feedstock for producing fuels and other chemicals. CO_2 conversion to methanol can significantly reduce emissions. The FReSMe-process in steel plants can avoid around 60% of CO2 emissions, compared to 18% with conventional capture methods [136].

5.4.3 Quantify the conversion of CO_2 into methanol

The carbon cycle consists of the natural production of carbon dioxide by all organisms and its recycling by plants during photosynthesis. The combustion of fuels in a variety of stationary and mobile energy systems also results in the unfortunate emission of CO_2. To create a net carbon neutral cycle (figure 5.6), CO_2 can be collected from both atmospheric and concentrated sources and transformed into liquid fuels. Different kinds of carbon are stored in four main reservoirs: CO_2 gas in the atmosphere biological components, such as forest cover; 2) Limestone-dissolved carbon dioxide in the ocean; 3) Rocks, sediments, and fossil fuels in the subsoil; and 4) Oceanic materials.

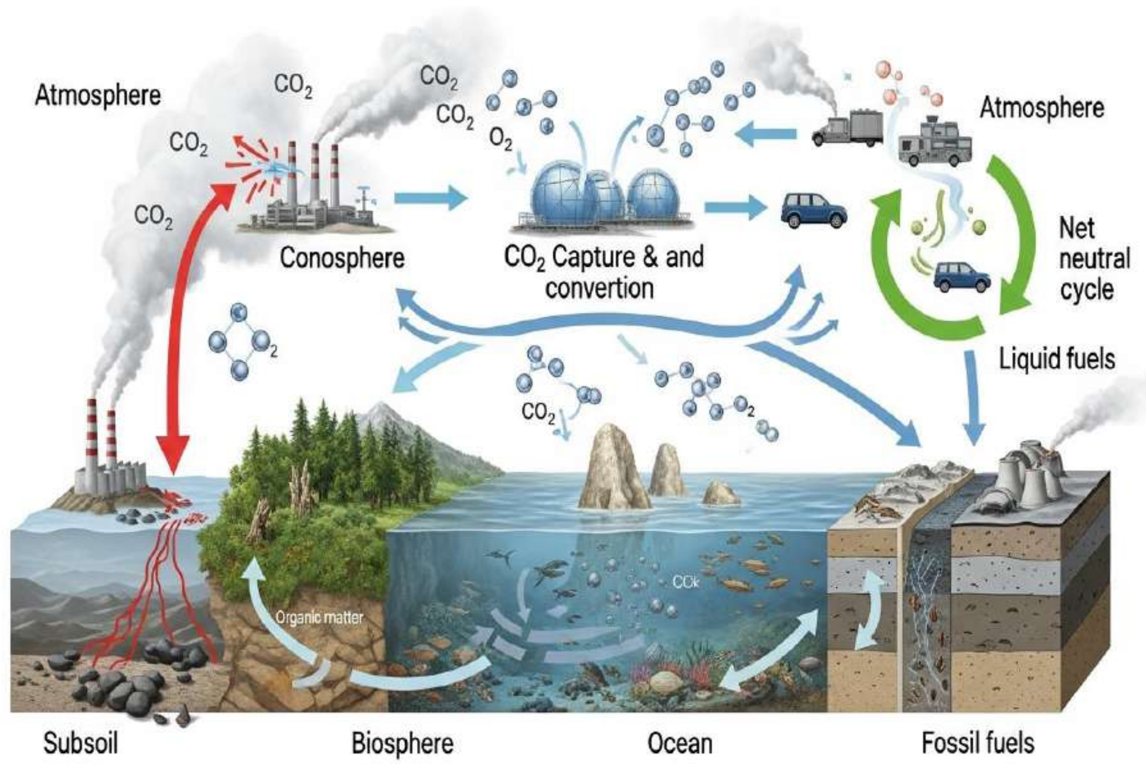

Figure 5.6 Carbon neutral cycle

As a result of human activities like burning fossil fuels, which include organic carbon, the natural carbon cycle, which consists of carbon fluxes between various reservoirs, is disturbed. New technologies using the renewable sources as a solar energy conversion into chemical energy by cycling CO_2 in the industrial sector [137]. Accordingly, CO_2 an energy for the future is a look in the recent years when there has been a significant increase in the amount of technology and ways contributing to lower emissions of carbon dioxide [138], including methanol production as a promising strategy for the manufacture of fuel from renewable resources, CO_2 and decarbonizes energy [139]. Through forward research, development, and demonstration, the CO_2 capture and separation sources can be executed [140]. Several scenarios were made for methanol synthesis from captured CO_2, which combine with renewable hydrogen from biomass, solar radiation and wind sources [141].

Figure 5.7 introduces a new scheme of CO_2 to methanol recycling that takes an input the energy consumption in form of fuel for each sub-sector and gives as an output CO_2 emission from each sub sector. The Sankey diagram efficiently depicts the mass and energy flows throughout the entire process. The system's inputs and outputs are quantified, revealing that 60% of total CO_2 emissions (28.18 MT) can be captured. The diagram depicts the capture of CO_2 and its subsequent photocatalytic conversion, providing 19.89 million tons of methanol and 570 678 TJ of energy.

If the method adopted is photo-catalytic reduction and to product the methanol using the solar energy, which the photo-catalytic reactor gives 655g of methanol for every 1kg of CO_2 captured equation (28).

$$CO_2 + 2H_2o + \text{Solar energy} \rightarrow CH_3OH + 1.5O_2 \qquad (28)$$

The purpose of this CO_2 conversion model is to assess the maximal reduction potentials of energy consumption and greenhouse gas (GHG) emissions for the non-energy industries in Algeria. The amount of methanol produced from CO_2 captured from Algerian's non energy industry is about 19.89 million tons (25.14 billion liters) of methanol with an energy value 570 678 TJ can be used it instead of the methanol coming from fossil sources.

According to Ministry of Energy and Mining, the amount of methanol produced from fossil fuel is 113 Mt every year, which less than 1% of methanol produced from CO_2 and also that amount could replace about 53% petroleum products.

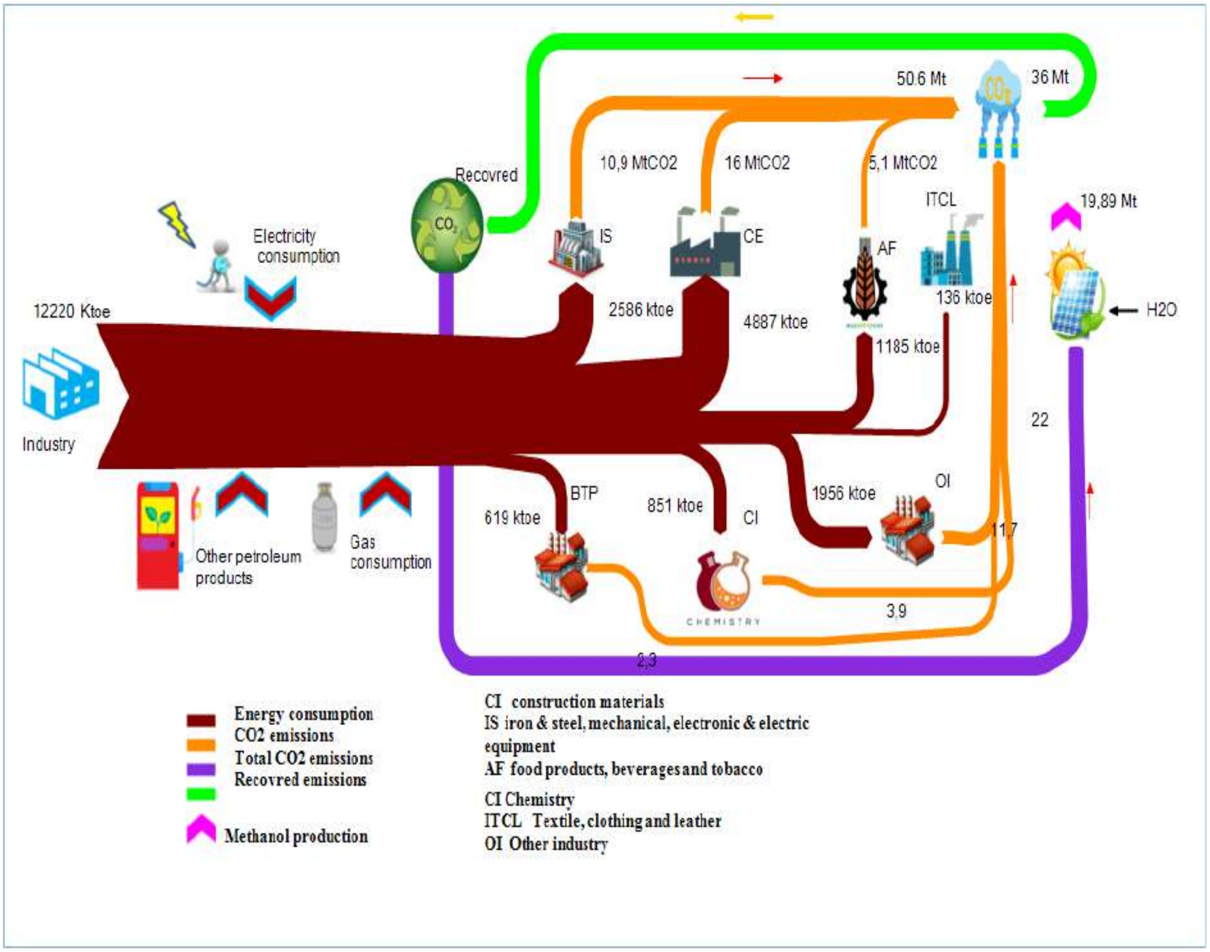

Figure 5.7 Sankey diagram of energy consumption, CO_2 emissions and methanol production in non-energy industries.

5.4.4 ARIMA forecasting of industrial CO_2 emissions and implications for mitigation strategies

The Autoregressive Integrated Moving Average (ARIMA) model is a widely used statistical tool for time series forecasting, particularly in predicting industrial CO_2 emissions. The effectiveness of ARIMA in this context hinges on its parameters; p (autoregressive terms), d (degree of differencing), and q (moving average terms). These parameters not only influence the model's predictive accuracy but also have significant implications for emission reduction strategies. The response explores how these parameters affect model performance and their subsequent impact on policy and strategy development.

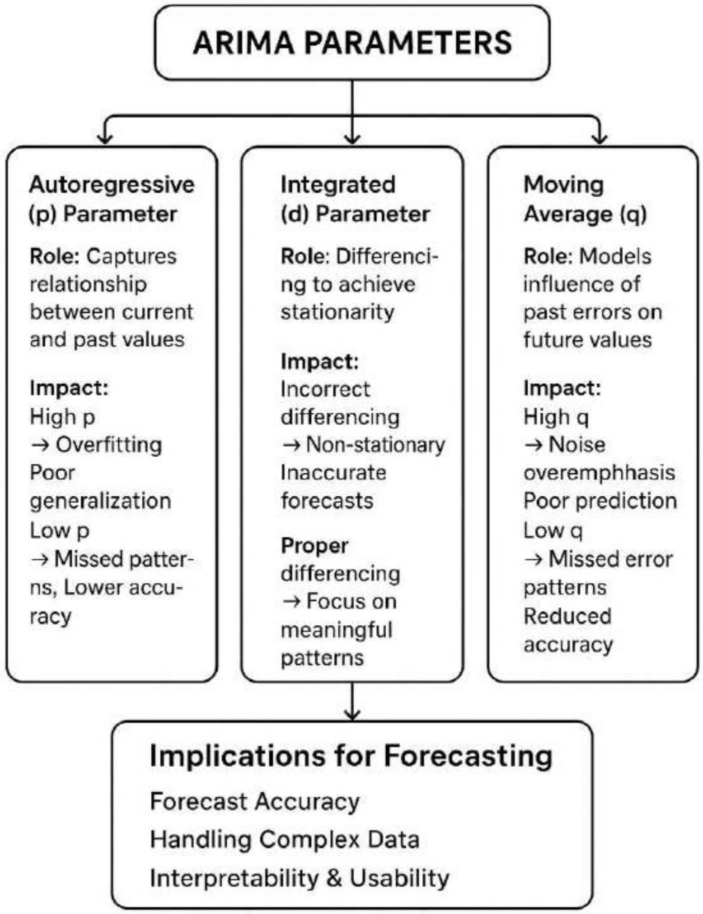

Figure 5.8 ARIMA primary parameters.

The parameters of an ARIMA model (figure 5.8) significantly influence its predictive accuracy and, by extension, the effectiveness of emission reduction strategies. The parameter selection, consideration of data characteristics, and integration with advanced techniques when necessary are essential for reliable forecasting. Policymakers can leverage accurate ARIMA models to design and implement successful emission reduction strategies, contributing to global sustainability goals.

The accuracy of ARIMA models in predicting industrial CO_2 emissions is influenced by several key factors, including the model's ability to handle data characteristics such as seasonality, nonlinearity, and randomness, as well as the integration of external variables and hybrid approaches. These factors are crucial in enhancing the predictive performance of ARIMA models, especially in complex industrial settings where emissions are affected by a multitude of dynamic and interrelated factors.

5.4.4.1 Data Characteristics

Seasonality and Nonlinearity

ARIMA models traditionally struggle with capturing nonlinearity and seasonality in data. However, incorporating seasonal dummy variables and nonlinear components can enhance their performance. A novel model that integrates these elements outperformed traditional ARIMA models in predicting CO_2 emissions across various sectors, achieving lower Mean Absolute Percentage Error (MAPE) values [142].

Temporal Dependencies

ARIMA models are adept at handling linear temporal dependencies but may require enhancements or hybridization to address complex patterns. Combining ARIMA with Long Short-Term Memory (LSTM) networks can compensate for its limitations in capturing nonlinear relationships [143-144].

5.4.4.2 Integration of External Variables

Operational and Environmental Factors

The inclusion of real-time process variables such as fuel type, combustion efficiency, and meteorological inputs can significantly improve the accuracy of ARIMA models. These variables help in capturing the external influences on emissions, which are crucial for precise forecasting [145].

Economic and Demographic Indicators

Factors like per capita GDP, industrial energy consumption, and urban development are also influential. Using techniques like Lasso regression to filter out less predictive indicators can refine the model's accuracy [146].

5.4.4.3 Hybrid approaches

Combining with Machine Learning Models

Hybrid models that integrate ARIMA with machine learning techniques, such as Support Vector Regression (SVR) or Back Propagation (BP) neural networks, can capture both linear and nonlinear features, enhancing predictive performance. These models have shown superior results compared to standalone ARIMA models [144] [146].

Weighted Model Combinations

Using weighted combinations of ARIMA with other models, such as Grey Models (GM), can reduce prediction errors and improve accuracy. This approach has been effective in specific industries, such as logistics, where it reduced prediction error by 4.33% [145].

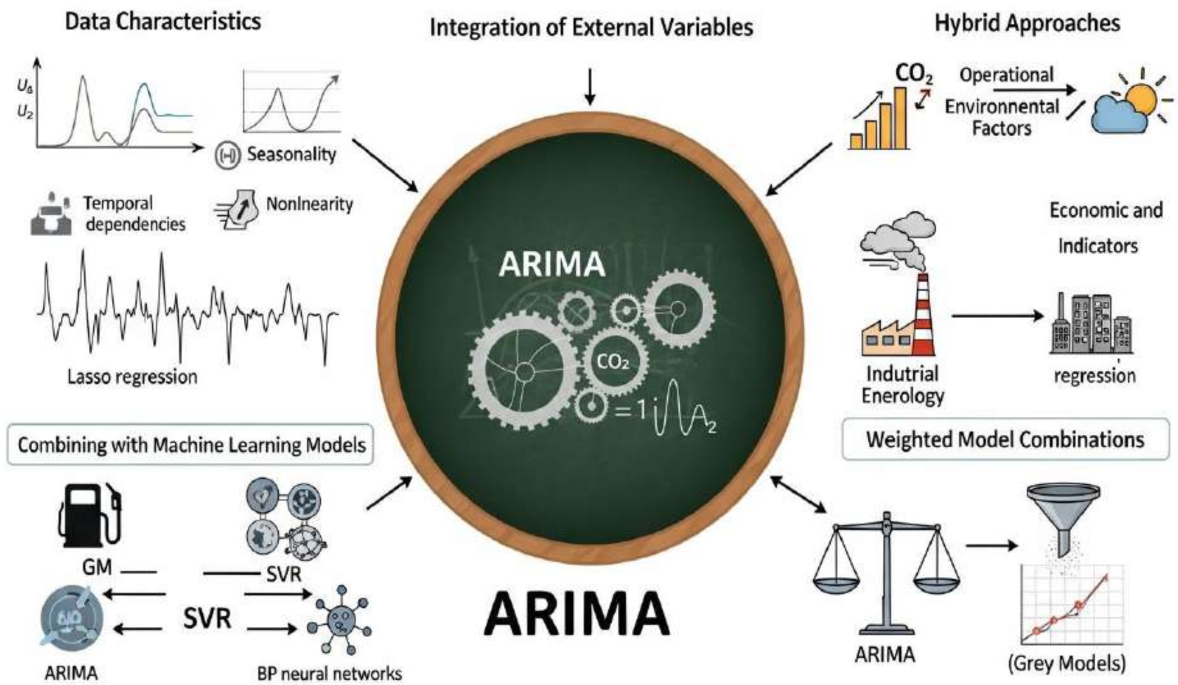

Figure 5.9 Data Characteristics of ARIMA models.

5.4.4.4 Model adaptability and scenario analysis

Scenario-Based Forecasting

The adaptability of ARIMA models to different scenarios, such as changes in industrial growth or environmental policies, is crucial for accurate predictions. Scenario analysis allows for the assessment of potential future developments and their impact on emissions [146].

Robustness and Validation

Systematic robustness verification frameworks are essential to validate the stability and reliability of ARIMA models, ensuring their applicability across various sectors and conditions [142].

5.4.5 Mathematical modeling to predict CO_2 emissions

The ARIMA (p, d, q) model describes a time series X_t based on past observations, past errors, and differencing techniques. The modeling is expressed as:

$$X_t = \sum_{i=1}^{q} \beta_i \epsilon_{t-i} + \sum_{i=1}^{p} \alpha_i X_{t-i} + \epsilon_t \tag{29}$$

$$\nabla^d X_t = \sum_{i=1}^{q} \beta_i \epsilon_{t-i} + \sum_{i=1}^{p} \alpha_i \nabla^d X_{t-i} + \epsilon_t \tag{30}$$

$$\nabla X_t = X_t - X_{t-1} \tag{31}$$

$$\tilde{X}_t = \nabla^d \tilde{X}_t + \sum_{i=0}^{d-1} \nabla^i X_{t-1} \tag{32}$$

Table 5.2 Parameters of ARIMA equations.

X_t	observation at time t.
ϵ_t	white noise (error term)
β_i, α_i	weight vectors
∇X_t	First-order differencing
$\tilde{X}_t$	Predict observation

5.4.6 Scenario analysis

The purpose of a scenario analysis is to anticipate potential events by testing different hypotheses regarding the persistence of an existing trend or occurrence. This analysis presents all existing variables and the varying rates of each element for all scenarios.

ARIMA modelling in Orange data mining, a data mining tool, provides an intuitive interface for performing ARIMA models, which can be evaluated to conventional ARIMA implementations regarding precision and computing efficiency. Conventional ARIMA models are recognized for their statistical attributes and adaptability in time series forecasting; though it sometimes necessitates batch processing and become highly computational, in particular in extended datasets. On the other hand, the implementation of Orange may utilize modern computational methods to improve efficiency.

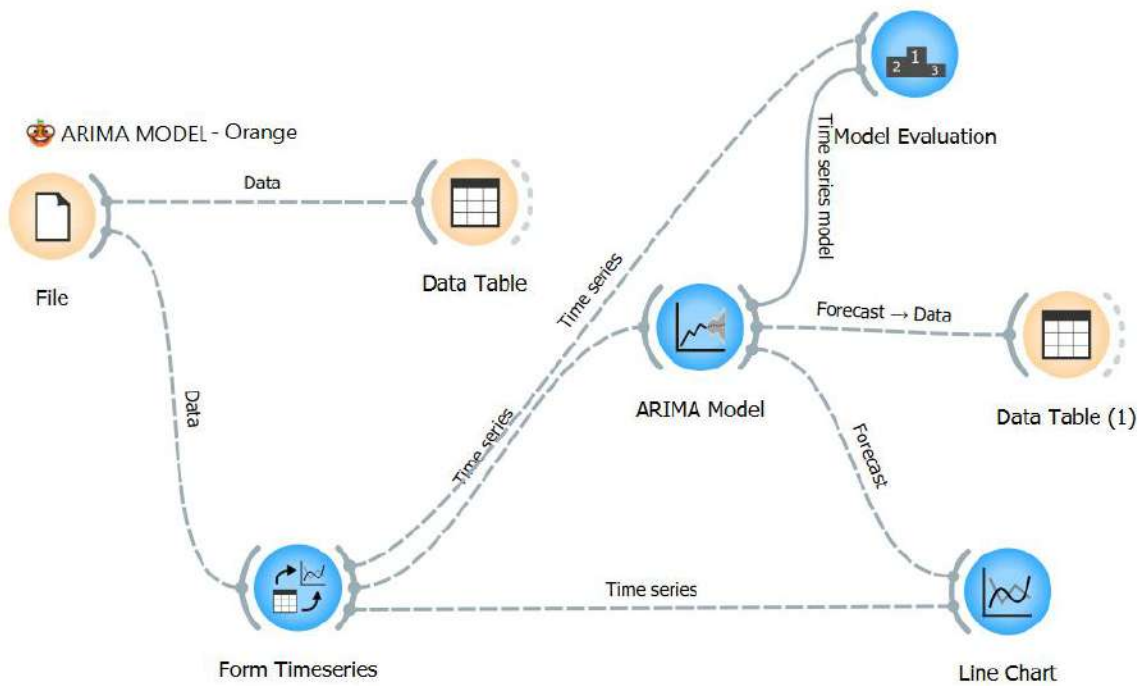

Figure 5.10 ARIMA Modelling using Orange data mining.

Conventional ARIMA models have been shown to provide high accuracy in various domains, such as economics and finance, but they can be outperformed by more advanced models like LSTM, which have shown a significant reduction in error rates [143] [147]. The inclusion of interacted lagged variables in ARIMA models can improve forecast accuracy when such interactions exist, suggesting that traditional ARIMA models can be enhanced for better performance. ARIMA-based models like SARIMA and SARIMAX have shown high accuracy with low error rates in specific applications, such as atmospheric pollution's forecasting in South Korea, indicating its utility in complex environmental data scenarios [148]. Independent ARIMA models built with frameworks such as MapReduce demonstrate enhanced computational efficiency, including ultra-long time series, by use of parallel processing capabilities [143]. The selfpaced ARIMA (SPARIMA) model mitigates instability from noisy data and enhances computational efficiency through a sequential training scheme, presenting a potentially advantageous method for Orange's ARIMA implementation [149].

Table 5.3 Descriptive analysis of CO_2 emissions (2006-2021)

CO_2 Emissions	Mean	Median	Std. Deviation	Min	Max	Skewness	Kurtosis
Non-energy Industry	37.37	35.49	7.43	25.92	50.60	0.24	-0.84
Transport	36.59	39.60	8.17	21.16	44.83	-0.81	-0.90
Total	142.32	146.76	26.75	103.19	178.80	-0.18	-1.60

Orange data mining offers an interface that enables users with limited programming expertise to implement ARIMA models without engaging in intricate coding (figure 5.10). The simplicity of use presents a notable benefit compared to conventional implementations that necessitate manual parameter tuning and specialized knowledge [150]. The auto-ARIMA feature in Python, equivalent to the features of Orange, accelerates the model selection process; however, it may not consistently surpass the accuracy of manually tuned models [151].

Table 5.3 illustrates the numerical findings from the descriptive analysis of CO_2 emissions in Algeria from 2006 to 2021, focusing on emissions from non-energy industries, the transport sector, and the overall energy-related emissions of the country.

Algeria's total CO_2 emissions average 142.32 Mt, ranging from 103.19Mt to 178.80Mt. The standard deviation (26.75) reflects considerable annual variations in total emissions, potentially which represents changes in industrial activity, transportation energy requirements, or economic expansion. The distribution exhibits moderate left skewness (-0.18) and is flatter than a normal curve (kurtosis = -1.60), indicate an extensive range of emission levels. The mean CO_2 emissions in non-energy industries are 37.37 Mt, with a range from 25.9 Mt to 50.6 Mt. The moderate standard deviation of 7.43 indicates minor deviation, indicating that emissions remain reasonably consistent across the observed years. The slight positive skewness of 0.24 implies a small concentration of lower emission levels. The CO_2 emissions from transport average 36.59, with variations ranging from 21.16 to 44.83. The observed negative skewness of -0.81 indicates an increase of higher emission values, coupled with an abundance of low outliers. The transport sector has a marginally higher level of variability (SD = 8.17) in comparison to emissions from industry. The data analysis highlights the crucial influence of the industrial and transport sectors on Algeria's CO_2 emission profile. The data indicates a necessity for specific mitigation plans in these critical areas to address Algeria's increasing energy-related emissions.

Table 5.4 Descriptive analysis of Methanol production scenario (2006-2021).

Mean	Median	Std. Deviation	Min	Max	Skewness	Kurtosis
14,69	13.95	2.92	10.19	19.89	0.24	-0.84

Table 5.4 presents the numerical results derived from the descriptive analysis of methanol production through the recycling of CO_2 emissions from non-energy industries for the years 2006 to 2021. The average methanol production from 2006 to 2021 was 14.69 Mt units, with a median of 13.95 Mt. Minimum output 10.19Mt and highest 19.89Mt indicate production range based on CO_2 recovery and conversion potential. Positive skewness 0.24 suggests greater production levels are slightly more frequent, showing methanol synthesis efficiency can improve. A negative kurtosis -0.84, indicates a flat distribution, reflecting operational flexibility and adaptability, as production values are widely spread rather than centered around the mean. The descriptive analysis of the methanol production scenario from 2006 to 2021 reveals stable production levels with moderate change, thus affirming its technical and environmental potential as a carbon recycling strategy. Integrating CO_2 capture with methanol synthesis enables Algeria to achieve two primary benefits; reducing greenhouse gas emissions and diversifying its energy and industrial production. The results reveal that ARIMA (1,1,1) were adequate model for forecasting of non-energy industrial CO_2 emissions.

Figures 5.11 and 5.12 present time-series of emissions under different mitigation scenarios from 2006 to 2035.

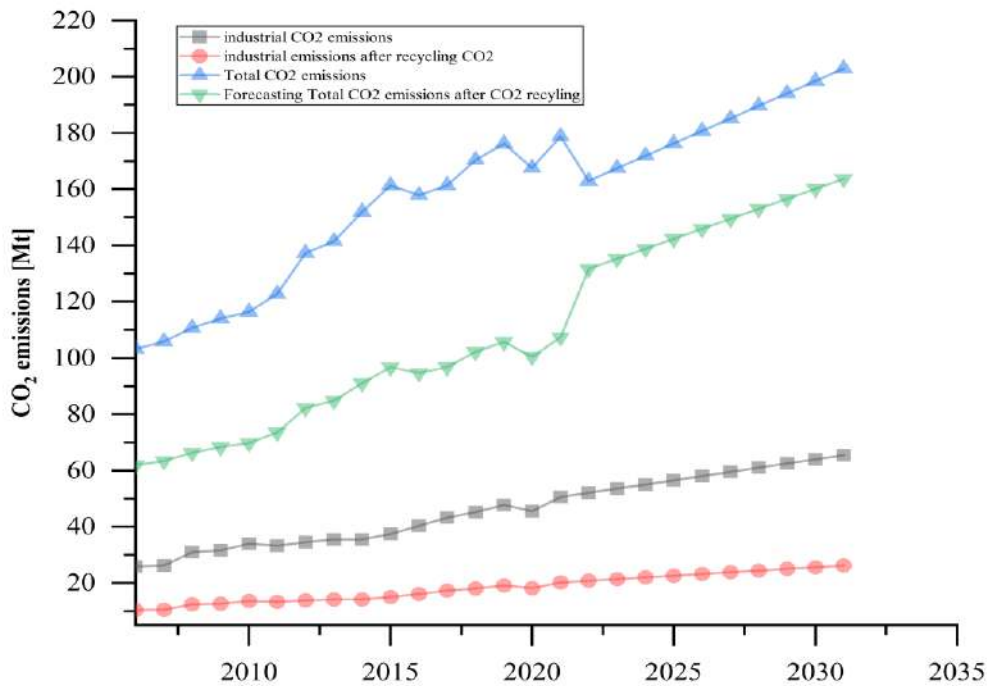

Figure 5.11 Scenario Analysis of Industrial and Total CO_2 Emissions in Algeria's Non-Energy Industries with and without Recycling (2006–2031) under Mitigation Scenario 1

The results suggest that scenarios incorporating CO_2 recycling to methanol yield lower cumulative and annual emissions than baseline or weaker mitigation cases. The findings employ scenario analysis to project the long-term environmental impact of implementing this technology.

Figure 5.11 illustrates the predicted increase in industrial and total CO_2 emissions in Algeria's non-energy sectors from 2006 to 2031, based on two divergent scenarios: a baseline scenario without of CO_2 recycling and a mitigation model that includes industrial CO_2 recycling. The paths indicate significant disparities in long-term emission results between the two scenarios. In the baseline scenario, both industrial and overall emissions demonstrate a continual increase. Total CO_2 emissions rise from 103 Mt in 2006 to 229 Mt by 2031, with significant short-term instability between 2015 and 2020, during which emissions oscillate between 157 and 176 Mt. Industrial CO_2 emissions exhibit an identical trend, increasing from 25 Mt at the outset of the period to 65 Mt by 2031. This consistent increase indicates the inherent emission intensity of Algeria’s non-energy industrial operations without further mitigating strategies.

However, the mitigation scenario with CO_2 recycling leads to a significantly slower rise in emissions. Industrial emissions after recycling increase only relatively, from around 20 Mt in 2022 to 26 Mt in 2031, resulting in a constant and low-emission trajectory over the projection period. Recycling increases overall CO_2 emissions from 132 Mt to164 Mt by 2031. These values are consistently and significantly lower than those observed in the baseline scenario.

At the end of the projected period for the scenario 1, the impact of CO_2 recycling on mitigation is substantial. The chart illustrates that the policy has a more significant impact on industrial emissions, the primary focus of the analysis, than on total national emissions, emphasizing that additional measures in other sectors are necessary for more profound decarbonization. The expanding divergence between the two trajectories illustrates the considerable promise of CO_2 recycling technologies in reducing emissions and facilitating Algeria's transition towards a more sustainable industrial framework.

The analysis is enhanced by incorporating a second, more optimistic scenario as depicted in figure 5.12. The chart represents the predicted pattern of CO_2 emissions in Algeria's non-energy sectors under Mitigation Scenario 2 from 2006 to 2031, comparing the baseline trend with the projected results after implementing mitigation strategies. This analysis evaluates three primary elements: industrial emissions, transport-sector emissions, and total CO_2 emissions, facilitating a thorough assessment of the scenario's effects. In the baseline scenario, all categories show a different and continuous upward trend over time. The transport sector demonstrates a significant increase, with emissions rising from roughly 21 Mt at the beginning of the period to over 36 Mt by 2031.

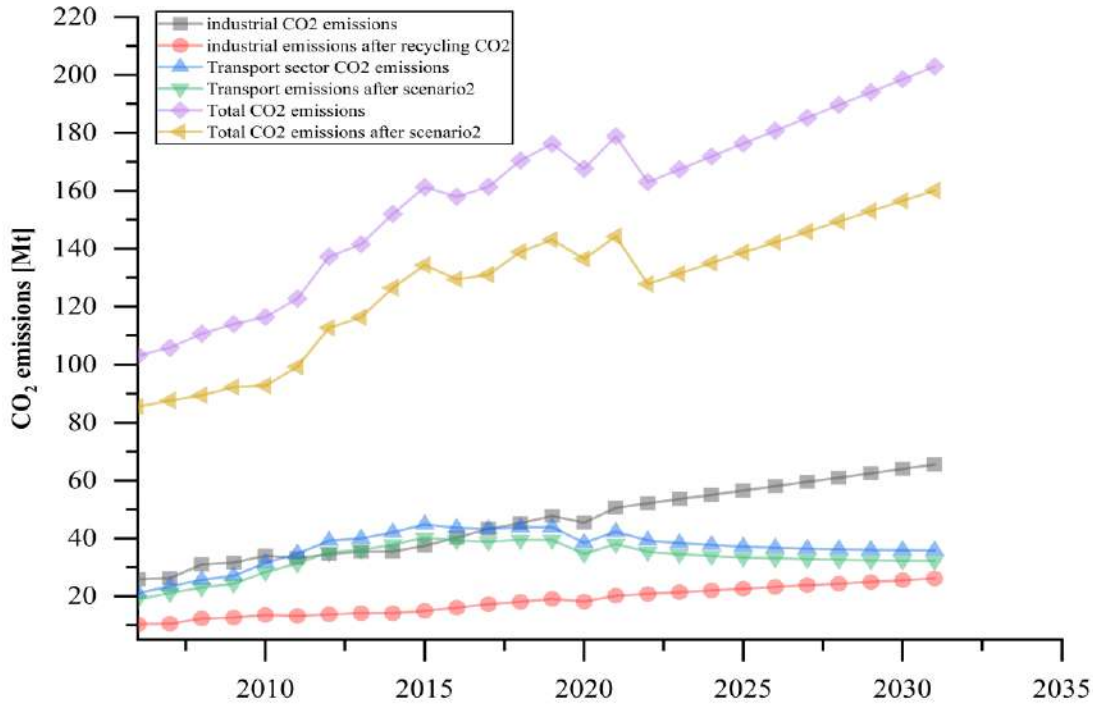

Figure 5.12 CO_2 Emissions in Algeria's Non-Energy Industries under Mitigation Scenario 2 (2006–2031).

In Mitigation Scenario 2, the emissions trends significantly diverge from the baseline. Emissions from the transport sector, post-mitigation, remain confined within a limited range between 32 and 35 Mt, indicating a significant divergence from the baseline trend. As a result of these reductions, total CO_2 emissions in the mitigation scenario decrease gradually, from 85 Mt at the beginning of the period to 160 Mt by 2031, consistently remaining far below the baseline trend throughout the projected period. The results examine emissions from the non-energy sector and indicates that, under Mitigation Scenario 2, more substantial reductions may be realized in comparison to Scenario 1. The application of these two scenarios constitutes a strong methodological framework; it evaluates various hypotheses concerning implementation efficiency and policy support, offering multiple potential futures instead of a singular deterministic result. This clearly conveys the impact of external factors on the results and the discussion regarding the effort needed to attain significant environmental benefits. The findings collectively present a strong visual argument, transitioning from technical feasibility to a quantified projection of emission reductions that corresponds with worldwide climate objectives.

5.5 Conclusion

The non-energy sectors of Algeria significantly contribute to CO_2 emissions, mainly owing to reliance on fossil fuels and increasing industrial processes. The provided CO_2-to-methanol conversion method offers a technically feasible and environmentally advantageous approach, with the potential for reduced emissions while supplying an effective energy source. Scenario analysis and ARIMA forecasts validate its considerable mitigation potential, emphasizing the necessity of combining these technologies with supportive policies to facilitate Algeria's low-carbon transition and fulfill with global climate commitments.

Global Conclusion

Global Conclusion

This thesis has examined the dynamics of energy consumption, CO_2 emissions, and energy recovery opportunities in Algeria's non-energy industries. Placed within the wider context of global energy challenges and Algeria's dependence on hydrocarbons, the study has focused on a sector that is often overlooked but increasingly significant for both economic diversification and environmental sustainability. By combining decomposition analysis, scenario modeling, and technological evaluation, the research has provided insights into the drivers of industrial energy use, the scale of emissions, and the potential for waste heat recovery and CO_2 valorization as practical solutions.

The analysis revealed that energy consumption in Algeria's non-energy industries has grown steadily over the past two decades, with industrial expansion serving as the principal driver. The Logarithmic Mean Divisia Index (LMDI) method showed that the activity effect, linked to economic growth, outweighed the limited contributions of efficiency improvements and structural changes. As a result, the industrial growth model has remained largely extensive, relying on output expansion rather than systematic efficiency gains. A similar pattern emerged in the analysis of CO_2 emissions. The growth of non-energy industries has translated into rising emissions, again dominated by the activity effect, with energy-intensive subsectors such as cement and steel identified as the main contributors. These findings underscore the challenge facing Algeria: non-energy industries are vital for diversification and employment, but they also impose an environmental burden that must be addressed.

The research further highlighted that Algeria's industries are characterized by considerable energy losses, particularly in the form of unused heat. International studies suggest that up to half of industrial energy inputs can be wasted in this way, and in Algeria, where many plants operate with outdated technologies, the proportion may be even higher. Transition to alternative fuel technologies therefore represent a powerful means of reducing both energy costs and emissions. Scenario modeling confirmed that capturing and reusing waste heat could enhance industrial competitiveness while contributing to national sustainability goals. Similarly, the thesis explored innovative mitigation strategies, focusing on the conversion of CO_2 into methanol. Although still at an early stage globally, this pathway holds significant potential in Algeria, where abundant solar resources could supply the renewable hydrogen needed for methanol synthesis. Such an approach would not only reduce emissions but also create new avenues for industrial diversification and value creation.

The contributions of this research are multiple. Empirically, it offers one of the first systematic studies of energy and emission dynamics in Algeria's non-energy industries, filling a notable gap in existing literature that tends to prioritize hydrocarbons. Methodologically, it applies the LMDI decomposition technique to disentangle the drivers of energy consumption and emissions, thereby providing a robust analytical framework for understanding industrial trends. The study evaluates the feasibility of recycling and CO_2 utilization in Algeria, showing their potential to transform challenges into opportunities. From a policy perspective, it formulates recommendations that could guide decision-makers in designing strategies to reconcile industrial growth with sustainability.

These findings carry important implications. Improving energy efficiency must become a priority for Algeria's industrial strategy, as efficiency measures remain one of the most cost-effective means of reducing energy demand and emissions. The country should also encourage the deployment of CO_2 utilization systems through financial incentives, public–private partnerships, and capacity building. At the same time, pilot projects in CO_2 utilization, such as methanol production, could lay the groundwork for long-term industrial transformation. More broadly, aligning non-energy industries with Algeria's international climate commitments would enable the country to contribute meaningfully to global mitigation efforts while enhancing its industrial competitiveness.

Nonetheless, certain limitations of the research must be acknowledged. Data availability remains a constraint, as industrial energy and emission statistics in Algeria are often fragmented or incomplete. Moreover, the feasibility of CO_2 utilization depends heavily on advances in renewable hydrogen production and cost reductions in emerging technologies. Institutional and policy barriers may also slow the adoption of energy efficiency and recovery measures. These challenges point to areas for future research, including detailed case studies of specific industrial facilities, economic modeling and assessments of the social and employment impacts of industrial decarbonization. Comparative regional analyses would also enrich the understanding of how Algeria’s experience relates to other countries with similar economic and energy profiles.

The research examines the potential of recycling CO_2 emissions from Algeria's non-energy industrial sector into methanol as a method to mitigate climate change. It emphasizes that non-energy sectors—specifically cement, iron and steel, and chemicals—constitute the predominant sources of Algeria’s CO_2 emissions (51%). This section illustrates a CO_2-to-methanol conversion process using photocatalytic techniques driven by solar energy, indicating that up to 60% of industrial CO_2 emissions (28.18 million tons) might be sequestered, yielding about 19.89 million tons of methanol and 570 678 TJ of energy. The ARIMA models is used for forecasting and scenario analysis indicates that the implementation of CO_2 recycling to methanol can substantially decrease cumulative and yearly emissions by 2031 relative to business-as-usual scenarios. The analysis highlights the technical viability and ecological advantages of this method, while also stressing the necessity for supportive policies, technological integration, and intersectoral collaboration to optimize emission reductions and advance global climate objectives.

In closing, this thesis has shown that Algeria’s non-energy industries occupy a pivotal position in the country’s economic and environmental future. They are at once engines of growth and major contributors to rising energy demand and CO_2 emissions. While the dominance of the activity effect reflects the structural realities of industrial expansion, the potential for change is significant. By embracing waste heat recovery, improving efficiency, and pursuing innovative CO_2 utilization pathways, Algeria can transform its non-energy industries into drivers of sustainable development. Doing so would not only reduce the nation’s environmental footprint but also strengthen its resilience and competitiveness in a rapidly changing global energy landscape.

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Appendix

Appendix A: Descriptive analysis of statistical Data

The visual representations enhance the descriptive analysis by illustrating variability, central tendencies, and overall patterns within the dataset.

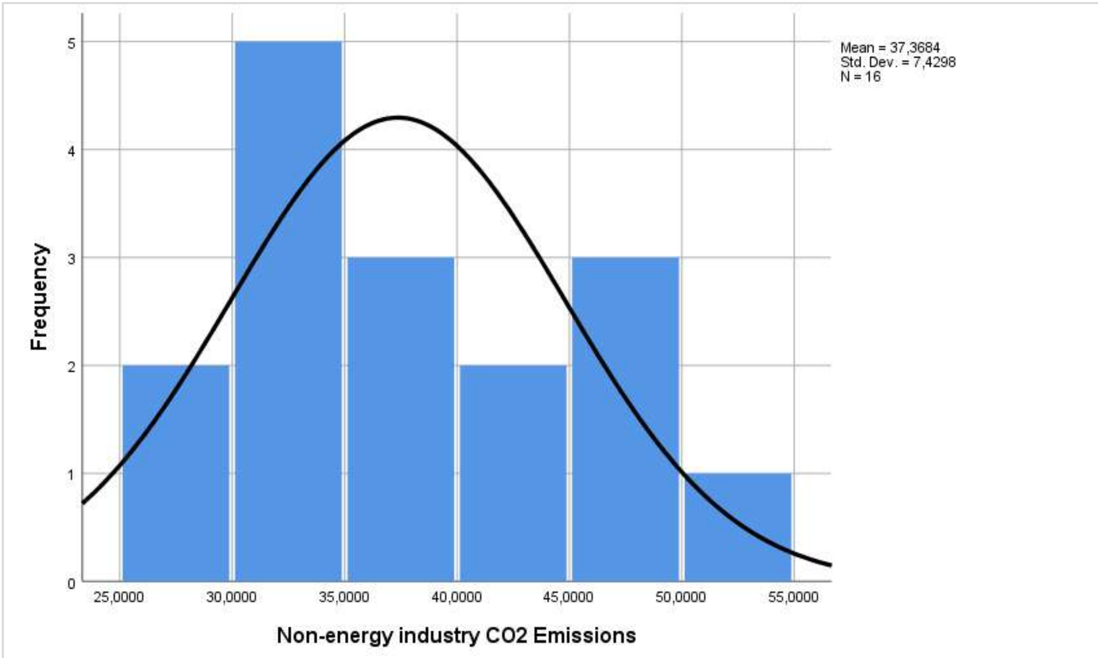

Figure A. 1 Non-energy industry CO_2 emissions (2006-2021).

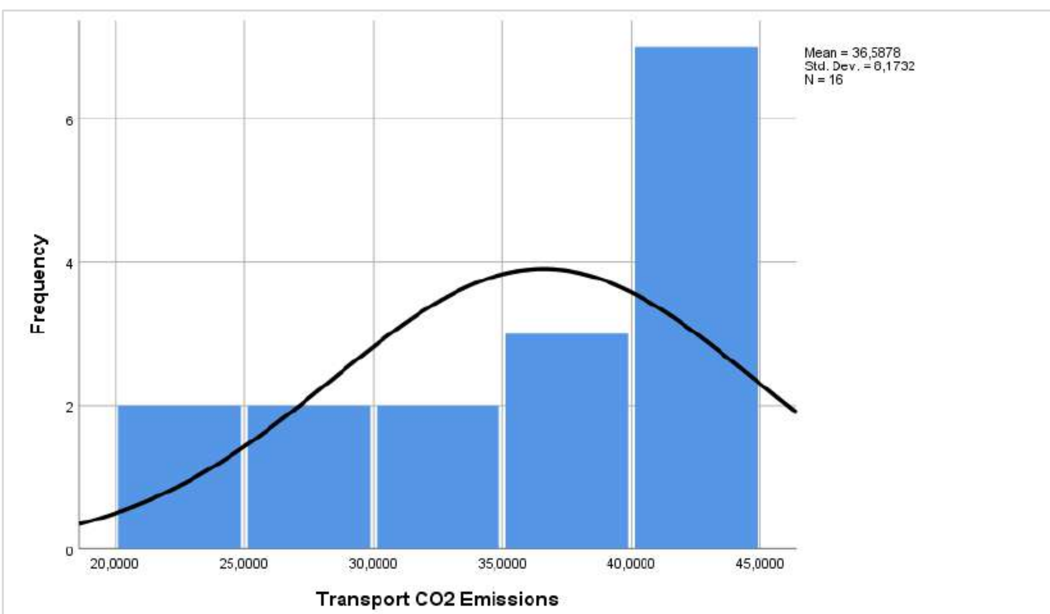

Figure A.2 Transport CO_2 emissions (2006-2021).

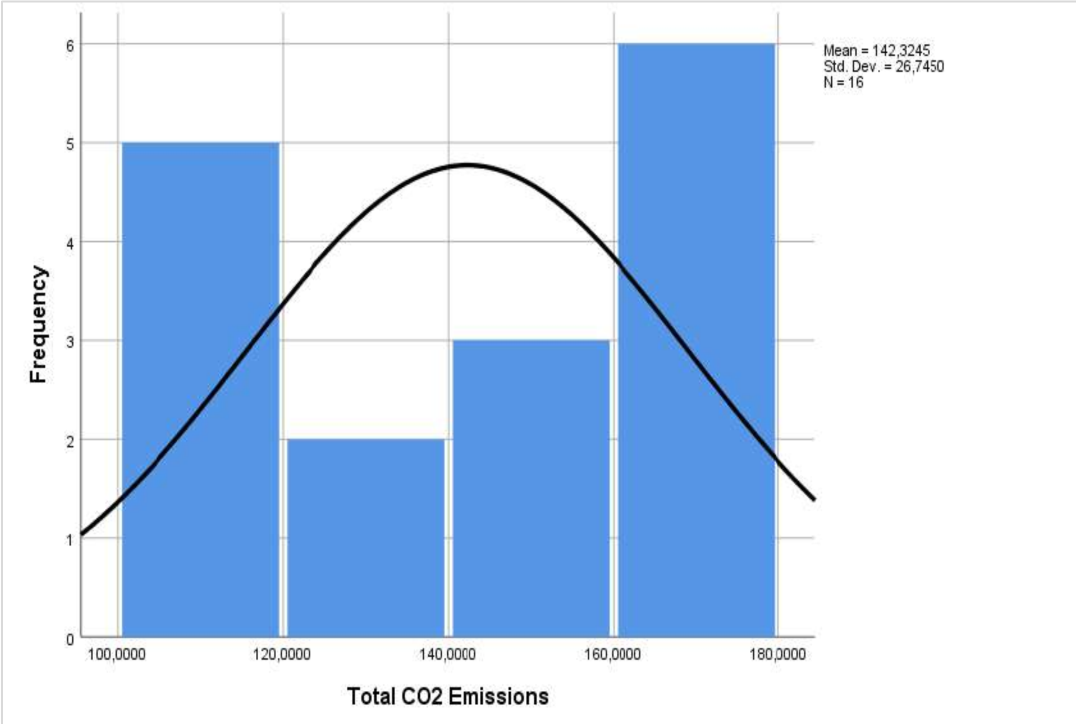

Figure A.3 Algeria's CO_2 emissions (2006-2021).

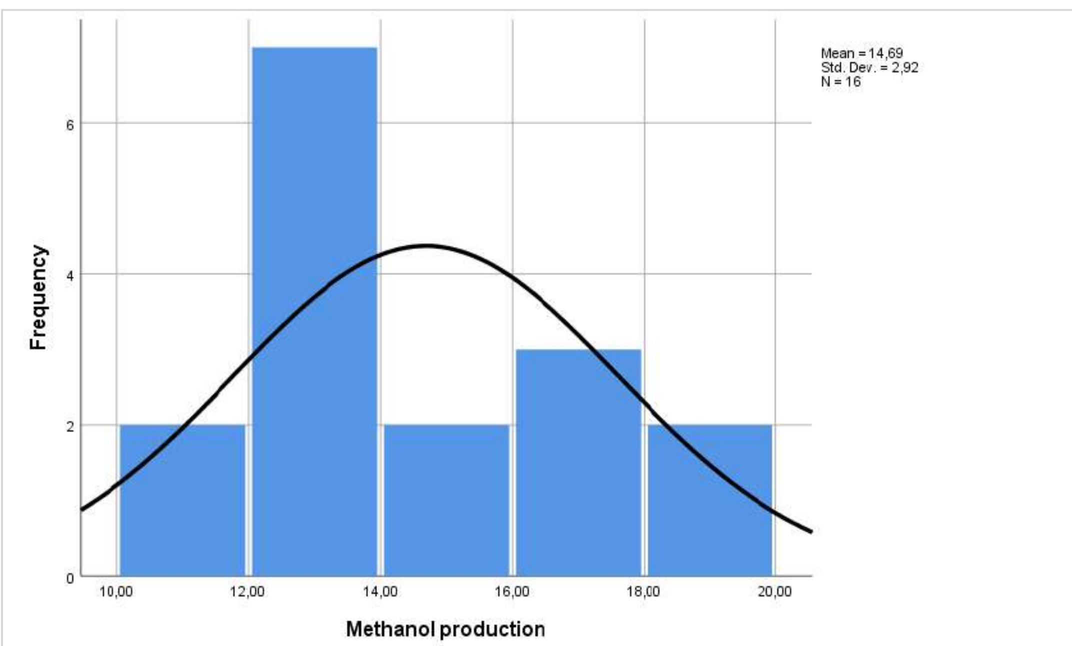

Figure A.4 Methanol production Scenario (2006-2021).

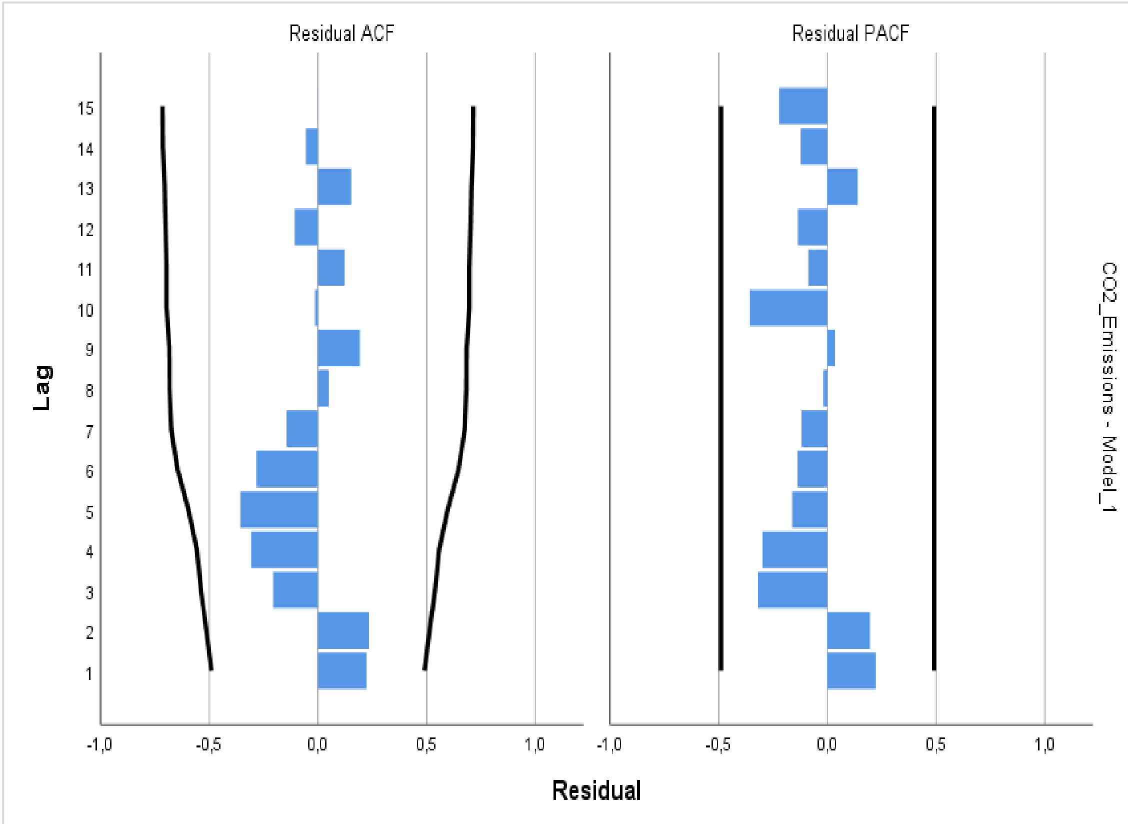

Figure A.5 Correlogram of industrial CO_2 emissions (2006-2021).