The Potential for Carbon Capture and Utilization (CCU) for the State of Kuwait

Thesis by

Asmaa Dh H Sh A Almutairi

This thesis is submitted for the degree of Doctor of Philosophy

Sir Joseph Swan Centre for Energy Research

Newcastle University

Newcastle upon Tyne

United Kingdom

28 February 2022

Abstract

Carbon Capture and Utilization (CCU) is a crucial enabling technology that supports delivery of the dual challenges of maintaining fossil fuels as a key energy source, whilst simultaneously dramatically reducing the associated CO_2 emissions.

This thesis aims to develop a realistic database of CO_2 emission sources in the state of Kuwait. The research then investigates the potential of deploying CCU in Kuwait, currently one of the highest carbon emitting countries in the world.

After identifying the major sectors responsible for CO_2 emissions, both 'top-down' and 'bottom-up' approaches were used to aggregate data from these sectors. The Emission Factors (EFs) were acquired from open literature such as the Intergovernmental Panel on Climate Change (IPCC). The analysis then explored the stakeholders' inclinations towards CCU. Both qualitative and quantitative surveys methods were conducted in the form of focus group discussions and the Information- Choice Questionnaire (ICQ), respectively.

The Kuwaiti power sector proved to be the predominant stationary source of carbon dioxide (CO_2) emissions (42%) due to high regional demand for electricity and water. The chemical industry ranked second in this analysis with a significant share of CO_2 emissions (26%) which was attributed to heavy and energy intensive industries, and this was followed by road transportation (16%).

The total process emissions were covered in this analysis for the first time which explains the variation between the real carbon footprint of Kuwait 98 Mt CO_2/y and both the World Bank 91.03 Mt CO_2/ y (WBR, 2006) and International Energy Agency 69.82 Mt CO_2/ y (IEA, 2010b) with differences of 7.7% and 40%, respectively.

The geographical distribution of CO_2 emissions was analysed, showing that high emission facilities are clustered mainly in the southeast which is the predominant industrial area in the state. This distribution could potentially be favourable for the formation of a 'capture cluster' which could reduce the overall cost of carbon capture deployment as a route for a sustainable carbon mitigation practice. If the Kuwait government diversify its economy towards non-oil bases, the carbon footprint of the state will increase from 118 to 126 Mt/y.

Overall, there was a positive attitude among all stakeholders, across a number of different sectors, regarding the potential of deploying CCU technology. However, some technical and economic barriers should first be addressed in each of the sector facilities since they are not designed to be retrofitted with carbon capture units.

In general, limited flexibility in Kuwaiti facilities with regard to being retrofitted with CCU technologies, and the impact of this process on their efficiencies, represent the main technical obstacles in the State. In addition to the technical barriers of reusing the existing high-pressure natural gas infrastructure for CO_2 transportation and managing the injecting process of CO_2 into a deep saline aquifer. From an economic aspect, the economic burden of introducing this technology to various institutions in the country will vary significantly depending on the lifetime and operating conditions of the current facilities. Oxy-fuel combustion appears to be the most economically attractive technology with its cumulative cost equivalent to approximately one third of the cost of post-combustion.

The key actions required to fully understand the potential of CCU in the state of Kuwait include developing new environmental regulations, extending the scope of the analysis to include techno-economic analyses, deployment of more pilot plants for CO_2-EOR in the north of Kuwait, and carrying out field optimization studies for the saline aquifer reservoirs.

Acknowledgment

Grateful acknowledgment is made to my supervisors at Newcastle University, particularly, my main supervisor, Professor Tony Roskilly for his support and encouragement. My gratitude is extended to Kuwait National Petroleum Company (KNPC), Kuwait Institute for Scientific Research (KISR), and Kuwait Oil Company (KOC) for kindly making available the data used in this study.

Finally, I would like to thank all my family and friends for their encouragement and motivation to continue my studies.

Table of Contents

Abbreviation

AAC	Autoclaved Aerated Concrete
Al	Aluminum
ASU	Air Separation Unit
BF	Blast Furnace
BOF	Basic Oxygen Furnace
Bpd	Barrels of Crude Oil Per Day
BS	Booster Stations
C_3H_8	Propane
$CaCO_3$	Calcium Carbonate
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CET	Common External Tariff
CFP	Clean Fuel Project
CGC	Cracked Gas Compressor
CH_4	Methane
CHP	Combine Heat and Power
CKD	Calcinated Cement Kiln Dust
C_{min}	Minimum capacity
CNT	Cube Nano Tube
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2-EOR	Using CO_2 in Enhanced Oil Recovery
CSP	Concentrated Solar Power
DCCE	Dynamic Common Correlated Effect
D_{max}	Maximum distance
DME	Di-Methyl Ether
DRI	Direct Reduce Iron
DRM	Dry Reforming of Methane
DW	Desalinated Water

E&P	Exploration and Production
EAF	Electric Arc Furnace
EC	Electricity Consumption
EF	Emission Factor
EOR	Enhance Oil Recovery
EP	Electrical Power
EPA	Environmental Protection Agency
EX	Export to GDP ratio
FAO	Food and Agriculture Organization
FCC	Fluid Catalytic Cracker
FD	Ratio of private sector credit to GDP
FGD	Flue Gas Desulfurization
GCC	Gulf Cooperation Council
GC	Gathering Centers
GDP	Gross Domestic Products
GHGs	Greenhouse Gases
GIS	Geographical Information System
H_2	Hydrogen
H_2S	hydrogen sulfide
HCPV	hydrocarbon pore volume
HP	Hydrogen Production unit
HRSG	Heat Recovery Steam Generator
HVDC	High Voltage Direct Current
IAMs	Integrated Assessment Models
ICQ	Information -Choice Questionnaire
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Rights
ITM	Ionic Transport Membrane
KEPA	Kuwait Environment Public Authority
km	Kilometers

km^2	kilometers square
KNPC	Kuwait National Petroleum Company
KOC	Kuwait Oil Company
KPA	Kuwait Ports Authority
kPa	Kilopascal
KSA	Kingdom of Saudi Arabia
kV	Kilovoltage
LEDs	Low Emission Development strategy
LMS	Ladle Metallurgy Station
LCoE	Levelized Cost Of Electricity
MAA	Mina Al-Ahmadi
MAB	Mina Abdullah
MC	Monte Carlo
MEA	Mono- Ethyl Amine
MEW	Ministry of Electricity and Water
MF-resins	Melamine-formaldehyde resins
Mg	Magnesium
MMP	Minimum Miscibility Pressure
MMSCFD	Million Standard Cubic Feet per Day
MO	Ministry of Oil
MOI	Ministry of Interior
MSF	Multi-Stage Flash
Mt	Million metric ton
Mt/y	Million metric ton per year
Mtpa	Million metric ton per annum
MW	Megawatt
$NaAl_2OH$	Sodium aluminate
NO_x	Nitrogen oxide
NPV	Net Present Value
NRP	New Refinery Project
OC	Operational Capacity

OOIP	Original Oil In Place
PFCs	Per-Fluoro-Carbon gases
PMG	Pooled Mean Group
Ppm	Part per million
PSA	Pressure Swinging Adsorption
PUH	Process Unit Heaters
PV	Photovoltaic
R&D	Research and Development
RFG	Recycle Flue Gas
RWGS	Reverse Water-Gas-Shift
SCFD	Standard Cubic Feet per Day
SG	Specific Gravity
SHU	Mina Al-Shuiba
SLR	Sea Level Rise
SMR	Steam Methane Reforming
SO_2	Sulphur Dioxide
SOF	Solid oxide fuel cell
t	Metric tons
t/y	Metric tons/year
TDS	Total Dissolved Solids
TEU	Twenty-Foot Equivalent Units
TGRBF	Top Gas Recycling Blast Furnace
TSA	Temperature Swinging Adsorption
UC	Utilization Capacity
UF-resins	Urea-formaldehyde resin
UNCLOS	United Nations Convention on the Law of the Sea
VPSA	Vacuum Pressure Swing Adsorption
WBR	World Bank Report
WHO	World Health Organization

Table of Figures

Lists of Tables

Chapter 1: Introduction

1.1 Background

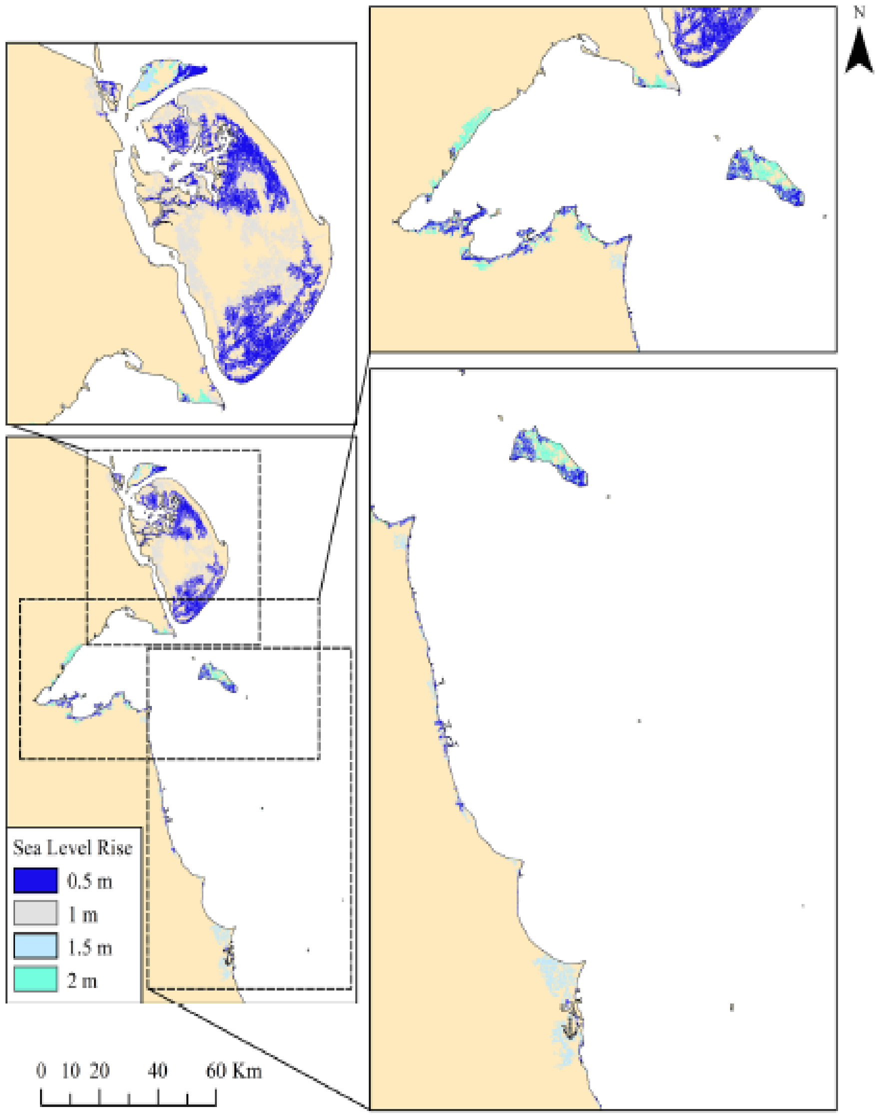
The State of Kuwait (hereinafter "Kuwait") is a member of the Gulf Cooperation Council (GCC) and is situated in the northwest of the Arabian Peninsula. This unique location has provided Kuwait with the opportunity to act, for a number of centuries, as economic hub between India, the horn of Africa, the Western Middle East and the Eastern Mediterranean rim countries. In 1945, oil was discovered in Kuwait and its exploitation altered the country from a tribal entity to a state with significant influence in international affairs.

Despite the relatively small land area of approximately 17,818 km^2, the territorial boundaries of Kuwait contained the world's fifth largest crude oil reservoirs. This resulted in the country experiencing remarkable economic growth during four decades with the rise in Gross Domestic Product (GDP) from USD 2.87 billion in 1970 to USD 55.66 billion in 2004 (Merza, 2007).

Kuwait has an arid subtropical climate due to its low annual rainfall and intensely hot summers with an average temperature of 44 °C (KEPA, 2019b). The prominent features of the Kuwait climate are humidity and dust storms with humidity regularly exceeding 95%.

An alarming fact is that a temperature increase of 2 °C has been recorded since 1957 and this is greater than the world average increase of approximately 1 °C (Mohammed, et al., 2013). In Kuwait, desalination is the only source of fresh water. However, this process ceases to operate if seawater temperature exceeds 38 °C, for safety reasons. Therefore, temperature increases could result in significant problems in terms of fresh water supply. Under a high emission scenario, the World Health Organization (WHO) anticipates an average rise of approximately 6.2 °C during the period 1990 to 2100 (WHO, 2016).

Another threat of climate change that will have a significant impact on Kuwait's socio-economic life is Sea Level Rise (SLR). The Kuwait coastline extends from the Kuwait-Iraq border in the north, a length of about 500 km, to the southern coast beside the Saudi-Kuwaiti neutral zone (Alsahli and AlHasem, 2016) (Figure 1). The special importance of the coastline comes from its intense urban, commercial, industrial, and recreational activities. As a result, flooding is expected to affect around 594,500 people in this area by 2100 (WHO, 2016).



-

Source: (Alsahli and AlHasem, 2016)

Figure 1. Effect of Arabian Gulf level rise on coastal areas in Kuwait

1.2 Kuwait Environmental Regulations

In light of Kuwait's vision to support international efforts and limit the negative impact of climate change, the Kuwait parliament has adopted the legislation: 'Environmental Protection 42/2014'. This law consists of 181 articles which are intended to control pollution in the state, encompassing protections of resources, human health, and living organisms (KEPA, 2016). Although Environmental Protection Law 42/2014 does not address Carbon Capture, Utilization, and Storage (CCUS) as a means of eliminating GHGs emissions, it has a number of general features that are consistent with the forming of the basis required for specific CCUS legislation.

Section (3): Protect the outside air from pollution

Articles 48 to 53 commit the Kuwait Environmental Public Authority (KEPA) to carry out regular monitoring and evaluation to maintain the air quality and reduce the harmful effects of pollutant gases (Appendix A). Furthermore, KEPA must coordinate with all the relevant authorities to prepare and develop a national strategy for air quality management and establish road maps for its implementation. From this perspective, all public and private sectors in the state are obliged to develop a monitoring and control system for air quality in the scope of their activities and not emit or leak air pollutants above the permissible limits. Based on the applied CO_2 captured, CCUS technologies can have a significant contribution in improving the conventional air quality through the following (Global CCS Institute, 2017):

- The deployment of flue gas desulfurization will lead to the elimination of approximately 90% of Sulphur dioxide (SO_2) emissions.
- Elimination of more than 70% of nitrogen oxide (NO_x) emissions.
- Total removal of fly ash from power plants.
- Control the percentage of heavy metals and particulate matter in the flowing gas.

Section (5): Management systems of KEPA

- Articles 122 and 123 discuss the mitigation strategies in the energy sector either directly or indirectly. These articles outline the critical requirement of deploying energy-saving systems in new state facilities. All the relevant authorities had insisted, in Article 111, on the adoption of these mitigation strategies, through the development of an action plan for both short and long-term effects.

All these environmental laws were developed to significantly reduce the state's greenhouse gas emissions and achieve the vision of His Highness the Emir of Kuwait by increasing the proportion of clean energy by 20% by 2030.

1.3 Carbon Capture and Utilization Related Conventions

Major environmental challenges cannot be addressed effectively without international co-operation. This co-operation translated into a series of international conventions that regulate all human interactions with the environment. Figure 2 illustrates the international and regional environmental conventions that have been signed by the Kuwait government.

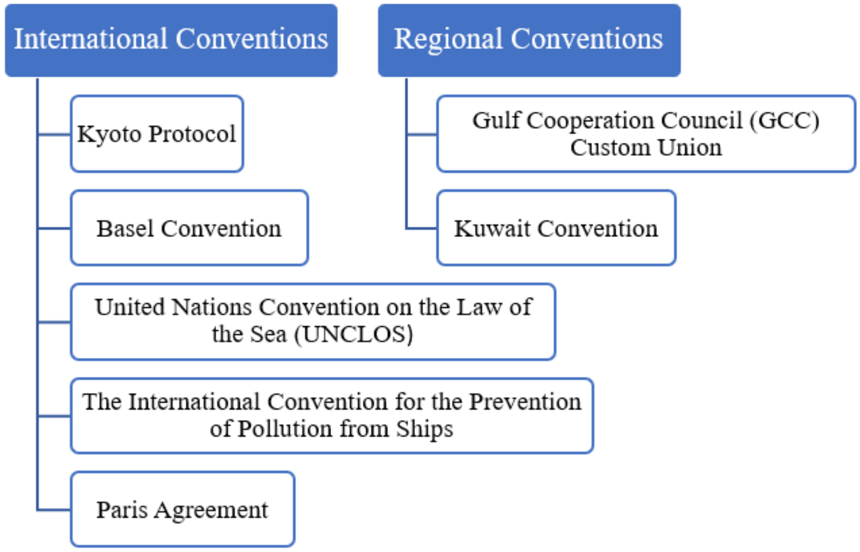


Figure 2. International and regional environmental conventions signed by the Kuwait government

1.3.1 International Conventions

A number of the relevant international conventions are summarized as follows:

- *Kyoto Protocol* is the first historical, global agreement to reduce the impact of climate change. It was negotiated in 1997 and came to force in 2005 (UNFCCC, 2021a). The protocol aims to reduce the emissions of worldwide greenhouse gases (GHGs) to 5.2% below 1990 level between 2008 and 2012, while the second commitment aims to achieve at least an 18% reduction between 2013 and 2020. Kuwait ratified the Kyoto protocol on 11 March 2005 (UNFCCC, 2021b).
- *Basel Convention*: Kuwait is among the countries that signed the Basel Convention in October 1993 (UNEP, 2011). It is the most comprehensive global environmental agreement that addresses the trade and disposal of hazardous waste (UNEP, 2021). The overarching objective of the convention is to minimize the amount and the level of toxicity of hazardous waste generated in the member nations, in addition to requiring environmentally sound processes for the transboundary movement of hazardous waste.
- *United Nations Convention on the Law of the Sea (UNCLOS)* agreement entered into force in 1994 and is known as ‘constitution of the ocean’. The convention lays down a comprehensive regime that covered many aspects of ocean affairs from scientific

research to navigation and fisheries. United Nations Convention on the Law of the Sea (UNCLOS) does not precisely control the activities of Carbon Capture and Storage (CCS) in the ocean but requires all partners to take all the necessary measures to eliminate ocean pollution. Kuwait was among the first countries that signed the convention in December 1982 and ratified it in May 1986 (United Nations Treaty Collection, 2021).

- *The International Convention for the Prevention of Pollution from Ships*: Kuwait signed before that another international convention in 1978 to safeguard the marine environment from ships (MC, 2019). Any leakage of CO_2 during ship transportation is defined, under this convention, as the leakage of harmful substances.
- *Paris Agreement* is the new version of the Kyoto protocol and came into force in 2016. The objective of the agreement was to exceed the Kyoto protocol, by aiming to achieve an increase of only 1.5 °C above the pre-industrial era, rather than 2 °C (United Nation Climate Change, 2015). Under the umbrella of this obligation, each member will review its policies to eliminate its national contribution and low GHGs emissions technologies will be transferred from developed to developing countries. The Paris Agreement focuses the government's attention on CCUS as it is the only technology capable of achieving this high level of elimination. In 2016, Kuwait signed the agreement and ratified it two years later, in April 2018 (UNFCCC, 2021b).

1.3.2 Regional Conventions

In addition to international conventions, two conventions are applicable in a regional context, as follows:

- *Gulf Cooperation Council (GCC) custom union:* implemented in 2003 to eliminate any restrictions on free movement of goods among GCC states. The union came about to achieve economic integration between the six Gulf countries, where there is a general agreement for Common External Tariff (CET) at 5%. The movement of captured CO_2 under this union will lead to the utilization of CO_2 in a more economically attractive way between these countries, especially for Enhanced Oil Recovery (EOR) purposes.
- *Kuwait convention*: another cooperation initiative between the GCC countries was undertaken as part of the Kuwait convention, which entered into force in 1979

(UNEP, 2014) and aims to protect the marine environment in the Arabian Gulf from any potential pollution. This comprehensive agreement obligates all its members to take the necessary environmental actions to eliminate pollution from ships, dumping, exploration, and exploitation.

1.4 Integration of CCUS Rules in Kuwait Environmental Regulations

The International Energy Agency (IEA) CCUS regulatory framework model was developed to provide consistency across different authorities around the world (Beck, et al., 2011). The model was designed to work with various legal and regulatory environmental rules. It addresses these regulations through four broad categories. Firstly, broad regulatory issues describe the interaction between the CCUS regulatory framework with climate change international laws, such as the transboundary movement of CO_2. Secondly, the existing regulatory issues can be applied to CCUS, beyond traditional CCUS operations, to include the environmental and human side effects. Then came the core focus of the model, which is the 'CCUS-specific regulatory issues' with fourteen regulations. Twelve of these regulations deal with CO_2 storage and the remaining two deal with CO_2 capture and transport. Finally, after identifying CCUS-specific regulations, some additional issues are likely to arise and be relevant to CCUS regulatory activities. Therefore, these issues will be classified as 'emerging CO_2 regulations', such as knowledge transfer and data sharing, particularly in the demonstration phase.

Regulatory gap in Implementing CCUS technologies in Kuwait Environmental Rules: Tsai (2014) analyzed the main regulatory gaps in Kuwait's environmental rules, which covered issues from the four categories (Figure 3). The following text is a summary of these issues and addresses the areas that need to be standardized in any future adoption of CCUS-related regulations in Kuwait environmental legislation.

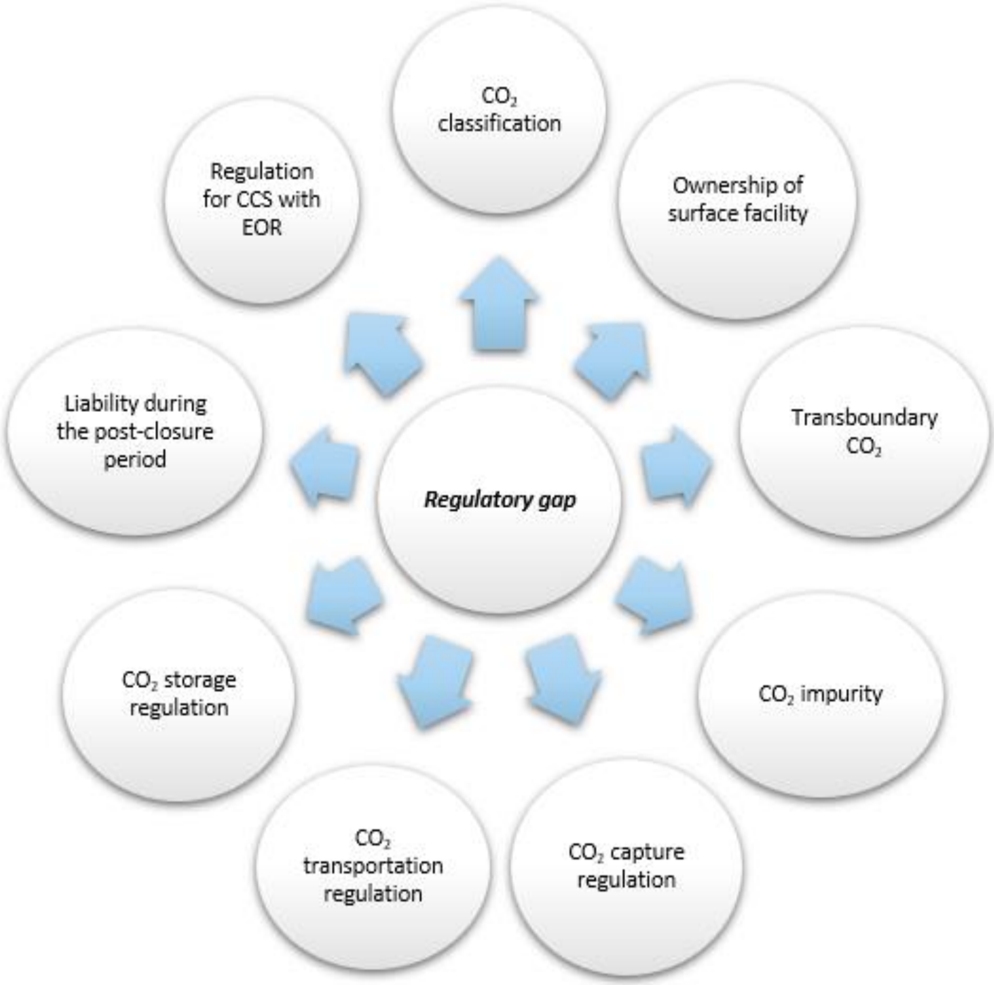


Figure 3. Regulatory gap in Implementing CCUS technologies in Kuwait Environmental Rules adapted from (Tsai, 2014)

- *Carbon dioxide classification*: the first step in identifying the potentially applicable legislation in the state is the classification of CO_2 as either a hazardous waste, pollutant, commodity, or combination. The way is classified will determine the regulatory framework for CO_2 under both national and international laws.
- *Property right*: after classifying CO_2, the concept of 'property rights' associated with CCUS projects needs to be clarified and this includes the capture and extraction facilities, in addition to the ownership of the surface and subsurface space. Developing CCUS legislation will protect CCUS operators from trespass and nuisance because of its use of the subsurface. Like most countries, this ownership belongs to the Kuwait government. Moreover, Intellectual Property Rights (IPR) should also protect knowledge sharing. The

greatest portion of CCUS chain exposure to IPR issues is the capture process due to its high cost and rapidly growing development rate.

- *Carbon dioxide impurity regulations*: as will be discussed in Chapter 5, CO_2 associated impurities should be first eliminated to meet the specifications of both transportation facilities and permanent storage. The type and concentration of these impurities will vary, largely depending on the source of the CO_2. All these variables and their potential technical impacts should be taken into consideration when adopting any CCUS impurities regulations.
- *Carbon dioxide capture specific regulations*: regulating the capture process of CO_2 in both the energy and non-energy sectors. These regulations should include laws regarding the introduction of the capture ready design for the planning projects, in addition to retrofitting existing projects with capture units.
- *Carbon dioxide transportation specific regulations*: once CO_2 is captured, it needs to be transported either to the oilfield for storage, for the purpose of EOR, or to the facilities for industrial utilization. Despite the specifications of any CCUS project, reliable, safe, and economically feasible systems are required to transport CO_2. Regulating the transportation process as well as pipeline re-use is required, in addition to illustrating the legal liability in the event of any leakage or damage yield from released CO_2.
- *Carbon dioxide storage specific regulations*: among all CCUS chain items, storing CO_2 represents the most effective climate change mitigation tool. These long-term benefits will not be achieved without effective regulations that manage CO_2 storage activities. Such activities include the exploration of storage sites, project inspection, monitoring, etc.
- *Knowledge transfer and data sharing*: exchange of knowledge and sharing of geological data from the demonstration phase, between experts, will have a significant role in moving towards full-scale deployment. This knowledge will include the technical barriers related to a specific region or country, the storage capacity of the existing storage sites, regulatory needs in this area, and the expected timeframe for deploying these projects.

All GCC countries have recently been associated with a high per capita carbon footprint. It puts them under scrutiny from other neighbouring nations and the world's industrial community (WBR, 2018). It forces them to consider innovative solutions to reduce their per capita carbon footprint without significantly affecting their economies.

Kuwait's government aims to increase the proportion of renewable energy by 20% in 2030. However, this percentage is not sufficient to eliminate the dramatic rise in CO_2 emissions associated with mega projects undertaken by the government, such as the New Refinery Project (NRF).

The scientific community recognizes CCUS as one of the critical enabling technologies despite the acceleration of renewable energy development. Since fossil fuel will remain the main source of energy in power and industrial sectors for many decades, CCUS is the only possible pathway to decarbonize these stationary sources (Banks and Boersma, 2015).

All global Integrated Assessment Models (IAMs) emphasized the role of CCUS in limiting the global temperature rise to 2°C Scenario (2DS) and Beyond 2°C Scenario (B2DS) (Budinis, et al., 2018). Integrated Assessment Models (IAMs) are used to provide policy-relevant insights about the technical and economic feasibility of any decarbonization strategy through analysing the data from many scientific disciplines (UNFCCC, 2019). For example, in the International Energy Agency (IEA) scenario, CCUS can participate in reducing 14% of cumulative CO_2 emissions in 2DS and 36% in B2DS through 2060 (Global CCS Institute, 2017). The United Nations Intergovernmental Panel on Climate Change (IPCC) model indicates that the cost of achieving the climate target will be nearly 140% higher in the event that CCUS technology is not deployed (IPCC, 2014).

Carbon Capture, Utilization, and Storage (CCUS) could balance the country's climate change international commitments, as described in Section 1.3, without hampering the government’s economic expansion plans. It is the only mitigation strategy that can deal with fossil-fuel stationary sources, the main source of CO_2 emissions in Kuwait. It is currently not possible to replace this heavy carbon legacy with renewable alternatives.

Furthermore, the vast oil reservoirs in the state provide a significant opportunity for using CO_2 in Enhanced Oil Recovery (EOR). The extensive analyses of the country stratigraphy and tectonic evaluation during oil exploration can pave the way for deploying this approach.

1.5 Research Objectives and Technical Deliverables

The work in this research project has several technical objectives that support the theme of the project: the study of CCUS potential in the state of Kuwait with the aim of minimizing carbon emissions from energy-intensive industries (*e.g.* petroleum downstream and chemical). The research objectives are as follows:

1.5.1 The potential to develop a realistic database of CO_2 emission sources in the state of Kuwait:

The existing published reports assessing the CO_2 emissions from the state of Kuwait focused mainly on fuel combustion and the cement manufacturing process, ignoring other emission sources. In light of this, the main goal of the first objective is to develop a more realistic database of CO_2 emission sources. This carbon atlas will provide a comprehensive analysis of all underlying sources of CO_2 emission in the state of Kuwait. The information developed because of this investigation will allow better-informed decision-making and limit the anthropogenic activities of carbon emissions. It represents the cornerstone for any mitigation strategy that may be adopted by the Kuwait government. The first objective will identify key questions that need to be addressed, including:

- What are Kuwait's CO_2 hotspots that have the potential to deploy CCUS technology?
- Are the published values from the international institutions representative of the real values of CO_2 emitted from Kuwait?
- How will the carbon footprint of the state be affected by the government's goal of diversifying its economy by 2030?

1.5.2 The potential to deploy CCUS technology in the state of Kuwait:

The aim of the second part of the research project is to investigate, for the first time, the opportunities, and challenges of CCUS technologies in Kuwait in the context of the environmental conventions signed by the Kuwait government. It complements the carbon atlas through the development of two scenarios for CO_2 capture. The first scenario suggests that all carbon capture and compression units are located at plant level in a decentralized location. In the second scenario, it is proposed that the entire flue gas stream with CO_2 content will be sent for treatment and compression in two-central locations in the Shuiaba and Al-Zour industrial areas. All technical and economic barriers will be discussed in detail. For policymakers, there are three critical questions surrounding the deployment of CCUS technologies in the state:

- What are the technical and economic barriers to deploy CCUS in the country?
- Can utilizing the CO_2 in the Enhanced Oil Recovery (CO_2-EOR) process motivate the deployment of CCUS in the country?

- To what extent are Kuwait saline aquifer reservoirs feasible for long term sequestration of CO_2?

1.6 Layout of the thesis

The remainder of the thesis will be organized as follows: Chapter 2: Literature Review, Chapter 3: Methodology, and Chapter 4: Development of the First Carbon Atlas of the State of Kuwait. Chapter 5: The Strategic Contexts for Carbon Capture in the State of Kuwait. Chapter 6: Policy Implementation and Chapter 7: Conclusion and Recommendations.

Chapter 2: Literature Review

2.1 Major Carbon Emission Sources

Since the Industrial Revolution, the global emissions levels of CO_2 have recorded a rise from 228 ppm in pre-industrial time to 400 ppm in 2013 (Leung, et al., 2014). It is one of the major end-products of conventional fossil fuel combustion that has a Green House Gases (GHGs) effect. In this case, it is called an anthropological CO_2 and differs from natural CO_2 which yields from natural phenomena (*e.g.* ocean-atmosphere exchange) (Figure 4).

A rapid rise in demand for fossil fuels over the next few decades, with the absence of effective alternatives, will lead to a sharp rise in the anticipated CO_2 emissions.

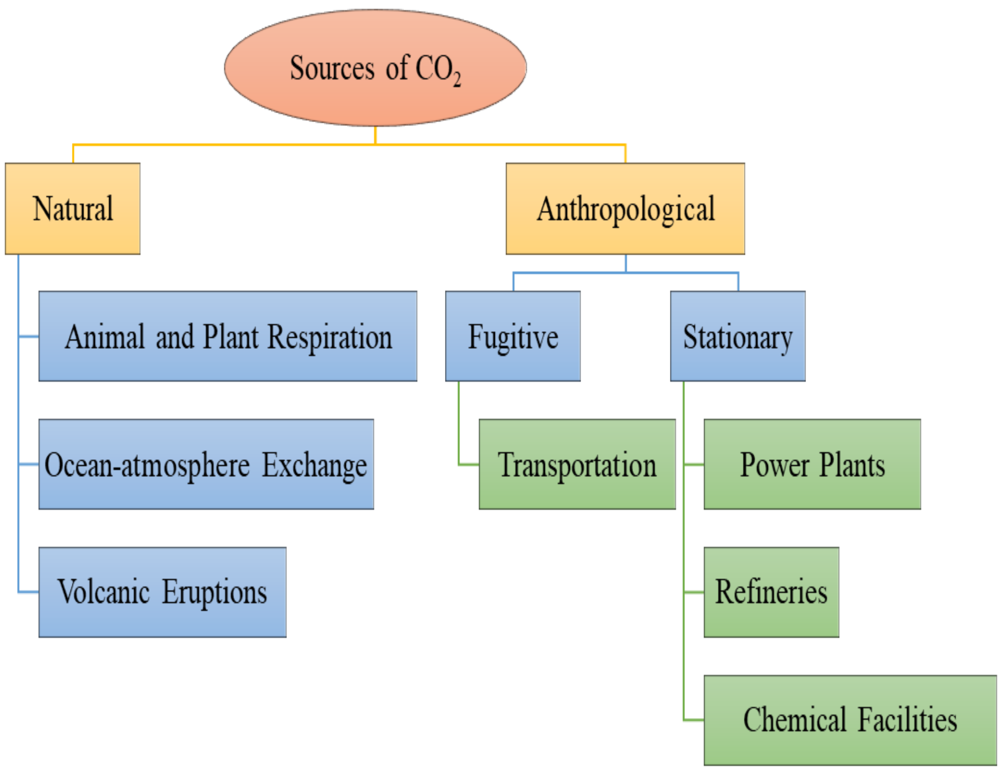


Figure 4. Natural and Anthropological sources of CO_2

All evidence to date indicates the potential for dramatic impacts because of climate change and this is forcing the international community, including Kuwait, to recognise the importance of deploying effective mitigation strategies.

Until 2040, fossil fuel is expected to remain the main source of energy globally, with a 50% share of gross electricity generation compared to 17% from renewables (Global CCS Institute, 2017). As a short-term solution, CCUS seems the only possible way to achieve a significant reduction in CO_2 emissions and continue to use fossil fuel in an environmentally sustainable manner. CCUS offers the opportunity to capture more than 90% of CO_2 emitted from fossil fuel power plants and large-scale industries and permanently store it underground for thousands of years to avoid its negative impact on the atmosphere (Banks and Boersma, 2015).

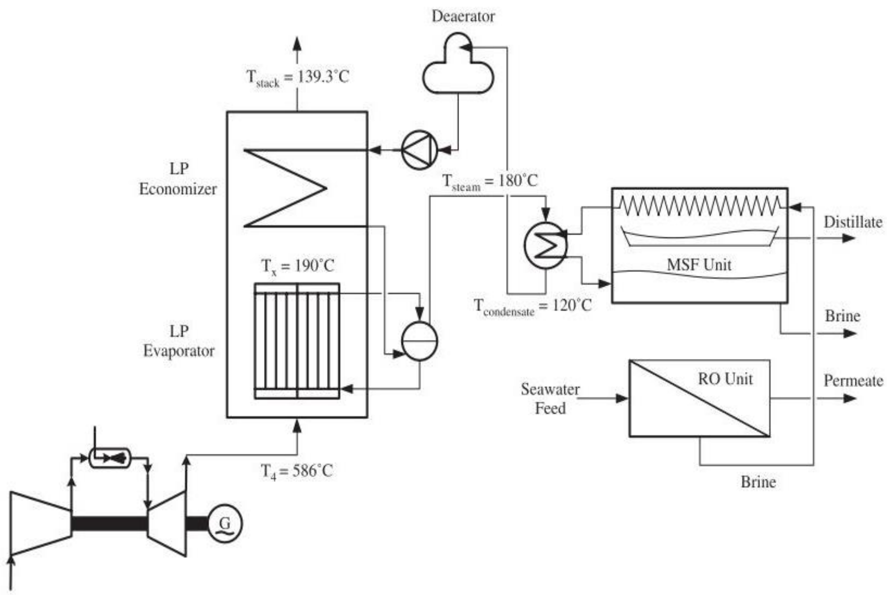
Between 2012-2050, no more than 884 Gt CO_2 can be allowed to be emitted into the atmosphere to meet the climate goals (IEA, 2013b). The amount of fossil fuel remaining within reservoirs that cannot be used is known as stranded assets. Carbon Capture, Utilization, and Storage (CCUS) provides the opportunity to extract these assets without the global temperature rising above 2°C (Clark and Herzog, 2014).

Moreover, several recent IAMs scenarios acknowledged the role of CCUS as an effective decarbonization strategy (Budinis, et al., 2018). The models were designed to help nations in adopting cost-effective environmental roadmaps. The IEA 2DS model identified CCUS as a game-changer technology with the potential of eliminating 14% of cumulative CO_2 emissions by 2060 (Global CCS Institute, 2017) while in the IPCC model, the total cost of any mitigation portfolio will be 140 % higher without including CCUS technology. Moreover, when coupled with bioenergy, known as Bio-Energy with CCS (BECCS), it delivers negative emissions where the historic CO_2 is removed from the atmosphere (Global CCS Institute, 2017).

To lay the foundation of this technology in any state; the amount of CO_2 emitted, and the geographical distribution of the potential storage sites will first need to be determined.

Power plants are the most common large stationary source, in addition to some chemical industries, such as oil refining. No research has been found that surveyed the existing carbon footprint of power plants in Kuwait; however, several scientific studies have been conducted which focus on developing the optimal configuration of the power plants (Hamoda, 2001; Darwish, 2005; Darwish, et al., 2008; Alotaibi, 2011; Savsar, et al., 2012). Figure 5 shows one of the recommended approaches through the introduction of a heat recovery steam system in the multi-stage flashing unit without additional fuel consumption. Increasing the installed capacity of these power plants will reduce the amount of fuel consumed and the anticipated CO_2 released.

Additionally, the potential of renewable sources in the state was also researched in (Al-Nassar, et al., 2005; Ramadhan, and Naseeb, 2011; Yessian, et al., 2013; Lude, et al., 2015). Improving power plant efficiency and using an alternative source of energy will contribute to eliminating CO_2 emissions but not a sufficiently significant amount that would result in a major reduction in the state's carbon footprint.



Source: (Darwish, et al., 2008)

Figure 5. Introduction of a heat recovery steam system to multi-stage flashing unit

As previously discussed, the Kuwait economy is heavily reliant on the petroleum industry. Petroleum production processes are further sub-divided in Chapter 4 into upstream, downstream, and petroleum-based industries.

The first preliminary analysis to estimate the carbon footprint of oil and gas extraction occurred in Norway (Gavenas, et al., 2015). The analysis was based on an examination of the effect of field-specific characteristics including oil price, CO_2 price, and time on the intensity of CO_2 emitted. An empirical model was developed for this purpose, followed by robustness and alternative estimation models to obtain a more precise picture. Equation 1 and Figure 6 outlines the driving forces that influence the intensity of the associated CO_2 emissions.

$$log(em\_int_{it}) = \beta_0 + \beta_{1a}prod\_share_{it} + \beta_{1b}(pro\_share_{it})^2 + \beta_{1c}(prod\_share_{it})^3 + \beta_3 gasres\_share_{it\_}\, \beta\ gasprod\_share_{it} + \beta_4 log(res\_size_i) +$$

$$\beta_4 log(res\_size_i) + \beta_5 log(res\_depth_i) + \beta_4 log(w\_depth_i) + \beta_\gamma water_{it} + \beta_8 log(carb\_p_t) + \beta_5 log(oil\_p_t) + \beta_{10}\, D\_elect_t + \beta_{11}\, start\_year_i + \beta_{12}\, time_i + C_i + U_{it} \quad (1)$$

Where *prod-share* is the percent of field historic peak production, *gasres-share* is the share of gas in the field's original reservoir, *gasprod-share* is the share of gas in the field's running production minus the share of gas in the original reserves, *res-size* is the original reserve size, *res-depth* is the reservoir depth, *w-depth* is the ocean depth, *water* is the water produced as a share of peak oil and gas production, *carb-p* is CO_2 price, *oil-p* is the oil price and *D-elect* is the dummy for the electric field. The first year of production is represented as *start-year* while the time trend is *time*. C_i is an unobservable field specific effect, U_{it} is genuine error terms while B_j is an unknown parameter. The value of *prod-share*, *gasprod-share*, and *water* are affected by both field type and time.

A key limitation of applying the Gavenas, et al. (2015) model in the Kuwait petroleum upstream processes is the lack of annual field data for CO_2 emissions. Moreover, two variables should be omitted from the equation, *w-depth,* and *carb-p,* because Kuwait neither extracts crude oil from the sea nor sets a price for CO_2. The other annual fields production data of crude oil, natural gas, and water, as well as reservoir characteristics, are available from Kuwait Oil Company (KOC).

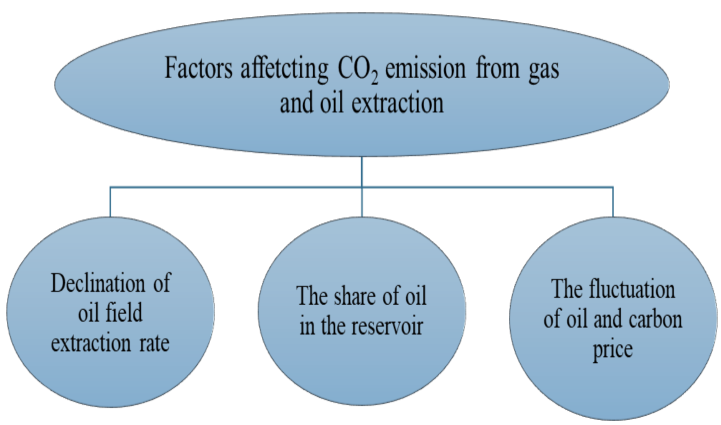


Figure 6. Factors affecting CO_2 from gas oil extraction adapted from (Gavenas, et al., 2015)

One of the major challenges of estimating the CO_2 emissions from the upstream production process is developing a reliable value of the emission factor, especially for the flaring process which is the main combustion process. This is due to the uncertainties of flared gas composition.

The reliability of the flaring emission factors values present in the CORINAIR database was examined in Martin, et al. (2003). Results showed significant variations between the actual value of the emission factor yield from the gas analysis system and the values available in the CORINAIR database. Locally, Al-Hamad and Khan (2008) investigated pollutants associated with flaring activities that occurred at Kuwait Oil Company (KOC). These undesirable emissions included nitrogen oxide (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO) along with CO_2. Figure 7 shows the geographical distribution of these emissions. In summary, all operations in oil upstream processes which occur in the state are emitting these pollutants, which demonstrates a need for an accurate estimation approach to help policymakers in KOC identify and implement the most appropriate mitigation strategy.

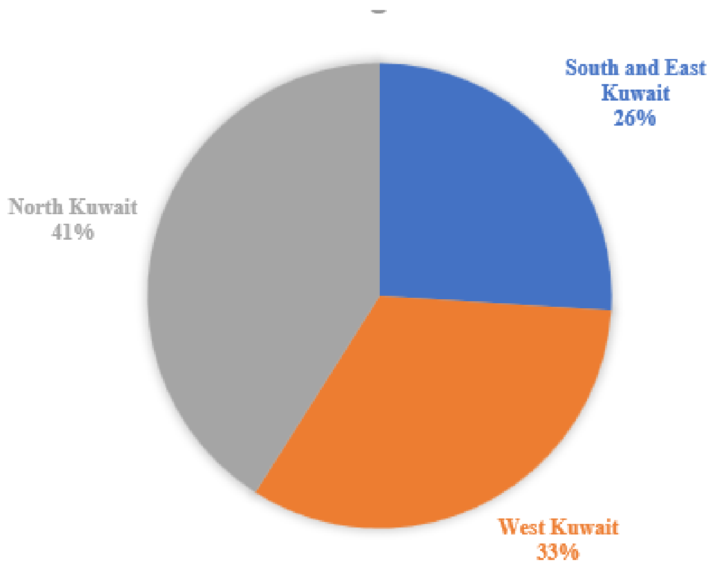


Figure 7. The geographical distribution of CO_2 emissions from all Kuwait oil fields in 1997, adapted from (Al-Hamad and Khan, 2008)

After the production process, the crude oil is sent to refineries to start the cracking operations. Limited research has been undertaken to address the CO_2 associated with these facilities. Among refinery units, furnaces and boilers are the largest contributors to CO_2 emissions due to the high numbers which exist in the typical refinery configuration. Utilities ranked second, followed by Fluid Catalytic Cracker (FCC) units, and then Hydrogen Production (HP) units (Van Straelen, et al., 2010). To illustrate the main driving forces of CO_2 emissions from refineries, a meaningful relationship was shown between the intensity of CO_2 emissions and the refinery's configuration rather than distilled products (Bredeson, et al., 2010).

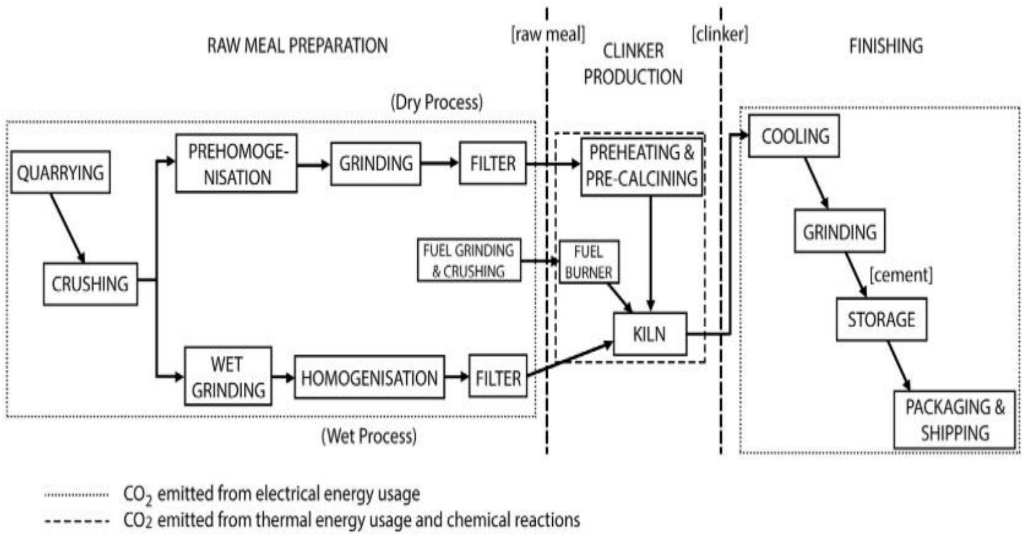
Locally, Al-Salem (2015) performed in depth numerical analysis of the carbon footprint of the three Kuwait refineries. The review covered: heaters, furnaces, flaring, HP unit, and Acid Gas Removal (AGR) unit. The results seem consistent with the Van Straelen, et al. (2010) review where fired heaters were responsible for 75% of the emissions followed by the HP unit (12-15%). The analysis also highlighted the roles of the New Refinery Project (NRP) and the Clean Fuel Project (CFP) in differing the carbon footprint of this sector in the state.

Some of the crude oil derivatives are used as the main fuels in power plants and vehicle transportation, while other derivatives will be further cracked in petrochemical factories. A comprehensive review of CO_2 emitted from Thailand's petrochemical industry indicates that fuel combustion, steam consumption, electricity consumption, and flaring were the main sources of the emissions (Kanchanapiya, 2015). Moreover, substituting conventional naphtha and ethane-based routes with coal and biomass are affecting the anticipated CO_2 emissions. The conclusive results have clearly shown a decrease in emissions when using biomass whilst also noting an increase when using coal (Ren and Patel, 2009). In Taiwan, an integrated methodology was developed to assess the energy use and CO_2 emitted from Taiwan's petrochemical industry (Lee, et al., 2001). Based on the research, the upstream petrochemical industry should be the primary target when attempting to reduce CO_2 emissions.

The Kuwait government's vision is to increase the petroleum downstream in order to achieve a marked position in the petrochemical market. Realizing all these relations will help the stakeholders in developing green petrochemical industries that meet global requirements.

Looking beyond the petroleum industry, the Intergovernmental Panel on Climate Change (IPCC) emphasized, in 2005, that the cement industry is the second-largest industrial source of CO_2 after electricity production. For this reason, it has been the subject of intensive international research, including in Europe (Mikulčić, et al., 2013), in U.S.A (Hanle, 2004), in Norway (Bjerge and Brevik, 2014) and in China (World Business Council for Sustainable Development, 2002; Lei, et al., 2011; Ke, et al., 2013) to eliminate its negative climate change impacts.

The major point sources of CO_2 emitted during cement production were reviewed in Ke, et al. (2013), Ishak and Hashim (2015) where the calcination process is identified as the hotspot of direct CO_2 emissions and electrical production for the indirect emissions (Figure 8).



Source: (Ishak and Hashim, 2015)

Figure 8. Carbon dioxide emissions during the cement manufacturing process

China was selected as a case study in various analyses such as by Shen, et al. (2014) that developed a bottom-up approach to determine China's cement Emission Factory (EF). To overcome the uncertainties which exist in the values published in previous reviews, the analysis developed a factory level measurement approach.

A historical investigation of CO_2 emitted from the China cement sector during the period 1990-2020 shows the potential of a 12.8% reduction in CO_2 emissions by incorporating advanced energy-related technology (Lei, et al., 2011). A comparison between three mitigation strategies, i.e., energy efficiency, alternative energy, and CCUS, demonstrates a potential of eliminating 57% associated CO_2, emitted through the deployment of a CCUS strategy by 2030, with 5-20% lower deployment cost than coal-fired power generation. The high percent of CO_2 emitted during the calcination process will offer economic benefits when deploying CCUS in Kuwait.

Previous research has shaped the debates in CCUS in heavy industries, in light of unprecedented economic growth in both developed and developing countries. The main hotspot for CO_2 emissions in the aluminium manufacturing processes was discussed in (European Aluminium Association, 2013; Colombia Climate Center, 2016; Bergsdal, et al., 2004; Ecofys, 2009; Harrison and Von Schéele, 2009) (Figure 9) while for steel and iron, research was carried out in (Skårman and Gustafsson, 2013; Pardo, et al., 2012; Carpenter, 2012; Sandberg, et al., 2001; Bellevrat and Menanteau, 2009; European Commission, 2013).

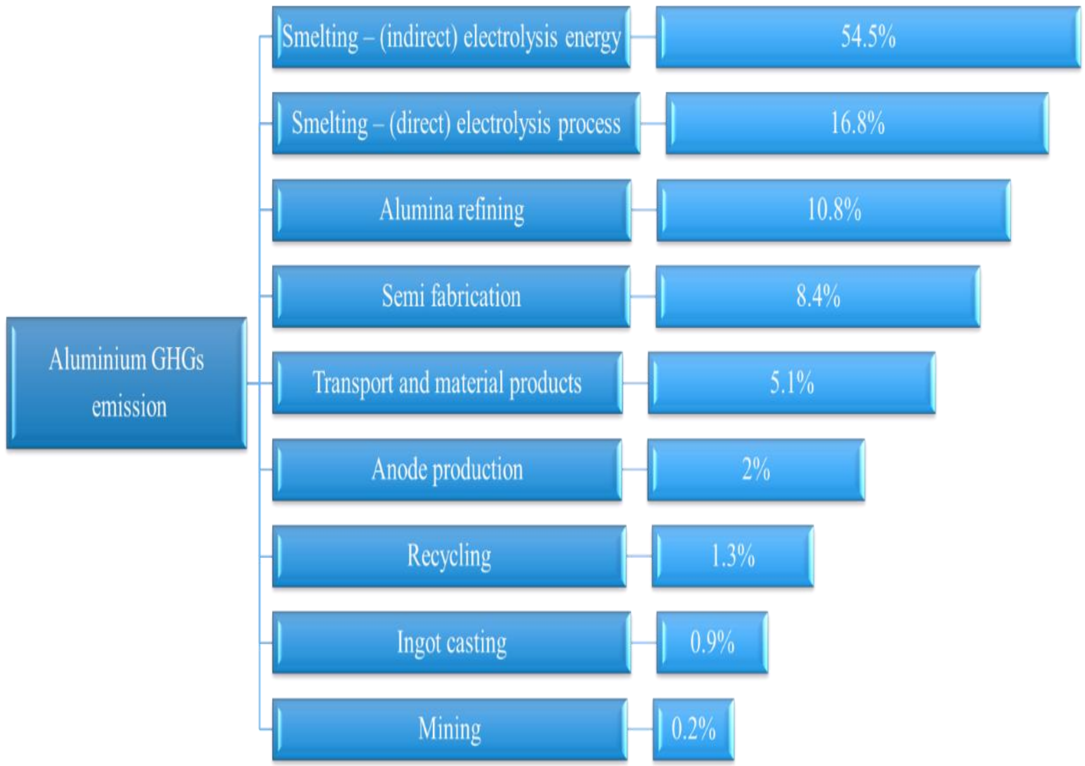


Figure 9. Greenhouse Gases (GHGs) emitted from aluminum industry adapted from (Colombia Climate Center, 2016)

Another analysis shows a considerable variation in CO_2 emissions in iron and steel industry in five South Asian countries: Bangladesh, India, Nepal, Sri Lanka, and Pakistan (Sarker, et al., 2013), due to differences in the type of fossil fuel.

The best available technologies and the rules for using these technologies to improve the environmental performance of the iron sector was covered (Zhang, et al., 2012; Johansson, 2014; and Kuramochi, 2016). Similarly, the Price, et al. (2001) review demonstrates that there is enormous potential to eliminate approximately half of the CO_2 emissions in five developed countries (Brazil, China, India, Mexico, and South Africa) through improving outdated technologies.

Through investigation, the carbon footprint of flat and long steel manufacturing in Sweden (Sandberg, et al., 2001), as shown in Figure 10, demonstrates the recommended approaches to reducing CO_2 emissions.

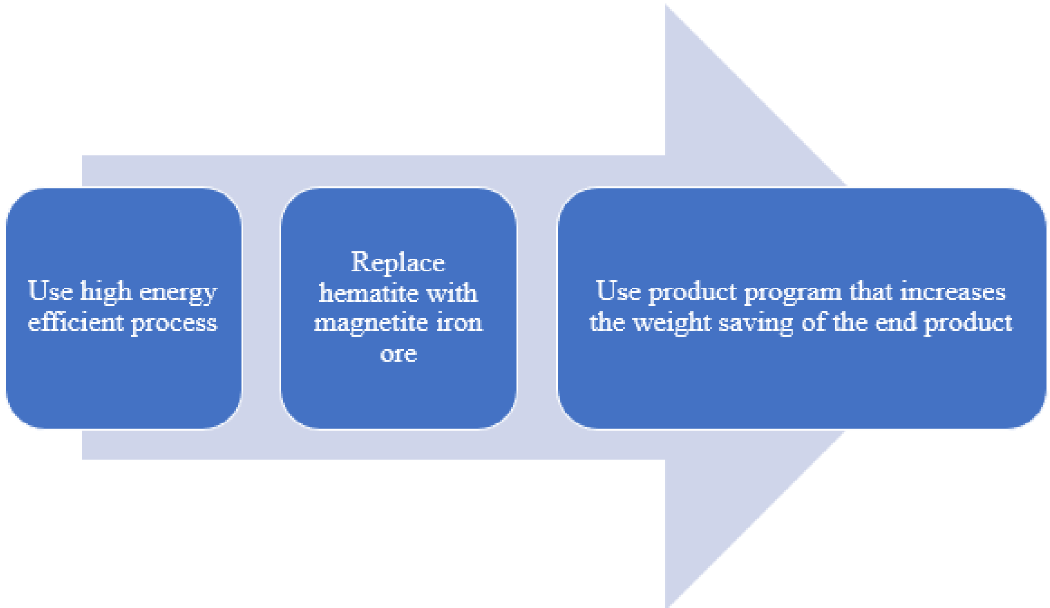


Figure 10. The recommend approaches used to reduce the CO_2 emissions from Swedish iron industry adapted from (Sandberg, et al., 2001)

As a first step for decarbonizing the chemical sector flue gas, several studies have been conducted to eliminate emissions by improving the current technology, including in the asphalt (Gibson, 2011; Gillespie, 2012), pharmaceutical industry (Galitsky, et al., 2008), detergent (Francke and Castro, 2013), pesticide manufacturer (Zero Waste Scotland, 2011) and plastic manufacture (Dormer, et al., 2013; Gunathilaka and Gunawardana, 2015).

The intensity of energy used in chemical factories has a significant impact on CO_2 emissions. After the petrochemical industry, fertilizer production, chlorine, and caustic soda were the major consumers of energy (Martin, et al., 2000).

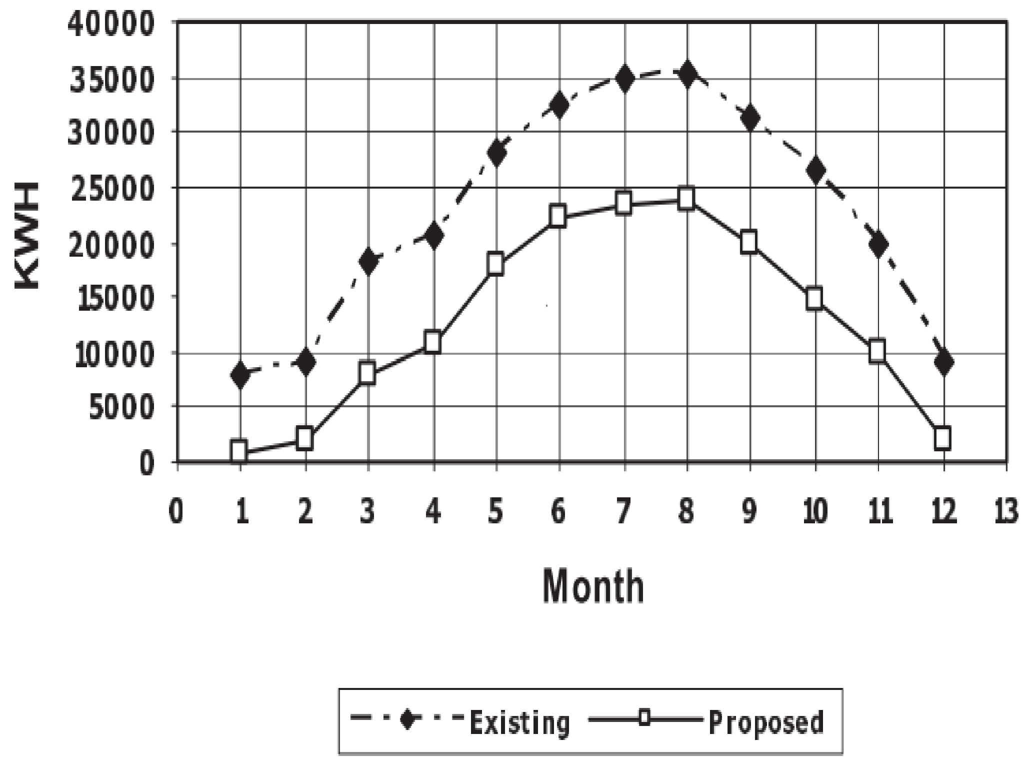
In a similar study to Martin, et al. (2000), a bottom-up analysis was used to estimate the energy used to produce the 52 most common chemicals (Neelis, et al., 2007). In Turkey, the primary pollutants released from industrial processes, including CO_2, have been estimated. The analysis only considered industrial emissions and excluded combustion activities. Seven main categories and 53 sub-sectors were studied with mineral and iron industries ranked as the largest contributors to these emissions, followed by organic chemicals, petroleum refining, pulp, and paper industry (Alyuz and Alp, 2014). Kuwait's government can take advantage of this research and analysis in efficiency improvements to the chemical sector, based in Kuwait’s industrial areas, in order to reduce the carbon footprint of these factories.

The studies discussed previously considered the carbon footprint of the main stationary sources. The following content will consider the main non-industrial end-users of energy. Buildings contribute approximately 40% of total global GHG emissions (Obafemi and Kurt, 2016). Three mitigation strategies have been emphasized by the Intergovernmental Panel on Climate Change (IPCC), starting with improving the efficiency of a building's electrical system (Biswas, 2014).

Locally, a framework was developed to evaluate the residential building stock models in order to allow the introduction of new green policies in this field (Jaffar, et al., 2014). Darwish (2005) analyzed the effect of improving the efficiency of the air conditioning (A/C) system, which uses approximately 75% of the energy used in a building. Various approaches that integrate building design and its mechanical systems have been developed for this purpose. Due to its religious significance with intermittent occupancy, Mosque was chosen to evaluate energy simulation software (Visual DOE 4.1) (Anzi and Al-shammeri, 2016). An energy reduction of approximately 70% could be achieved by improving the efficiency of Mosque electrical system.

Reducing the embodied energy of the structural system is the second crucial aspect in achieving a more sustainable construction sector. The embodied energy-based calculation was used to estimate this energy for various materials that are commonly used in different spans and columns (Griffin, et al., 2006) while bioclimatic principles are used for both pre-construction and construction stages (Sattary and Thorpe, 2012). In Bahrain, replacing the ordinary concrete used in residential buildings with Autoclaved Aerated Concrete (AAC) will reduce the CO_2 emitted by 5.2%. in comparison to a 1.2% reduction by using thermal insulation.

The final aspect is switching to renewable energy as illustrated in (Wortman, 1999; Fieber, 2005; Roos, 2009; Chaudhari, et al., 2013; Ma and Xue, 2013; Ibrahim and Atiyat, 2017). Locally, Al-Anzi and Khattab (2010) discussed the main limitations which exist in solar design and demonstrated the importance of using double glazing to conserve approximately half of the energy consumed (Figure 11).

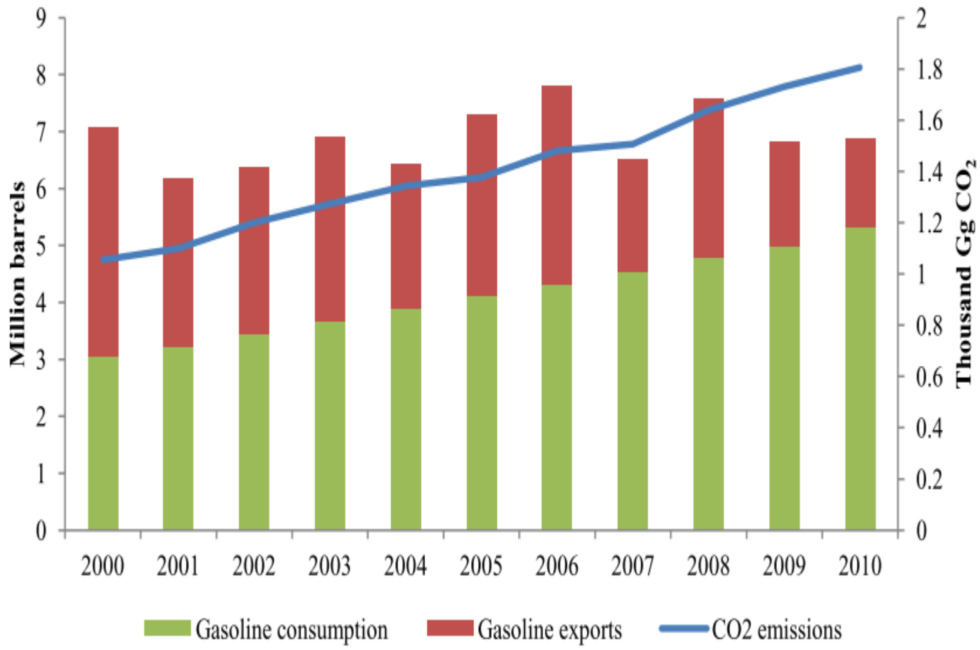


Source: (Al-Anzi and Khattab, 2010)

Figure 11. Energy simulation compression between the existing and proposed solar house designs

The transportation sector is an essential prerequisite for any social development. The main concern about this sector is its dependence on petroleum derivatives, which force governments around the world to issue standards and regulations for vehicles to save petroleum and eliminate CO_2 emissions. To estimate the carbon footprint of global passenger cars up to 2050, a high-level analysis was undertaken using a bottom-up accounting framework. Less developed countries will witness a significant rise in CO_2 emissions in comparison to more developed ones (Hao, et al., 2016). With the same objective, research was conducted in other regions and analyses included He, et al. (2005) for China, and Timilsina and Shrestha (2009) for Asia.

One of the first studies in GCC countries was completed in Bahrain to estimate the carbon footprint of private vehicles (Al Sabbagh, et al., 2013) (Figure 12). The analysis was undertaken despite a shortage of data relating to fuel economy and the average distance traveled by vehicles. By 2030, emissions are expected to have doubled compared to 2010. As a result of this analysis, providing a mitigation strategy has been of increasing importance in recent years.



Source: (Al Sabbagh, et al., 2013)

Figure 12. Development of gasoline consumption and CO_2 emissions from private vehicles in Bahrain

Introducing standards in fuel economy are expected to reduce approximately 27% of the anticipated CO_2 (Geffen, et al., 2003; Al Sabbagh, et al., 2013). This can be achieved by developing an energy system model (GET 1.0), to indicate when alternative fuels become an economically attractive option (Azar, et al., 2003). Scenarios were developed based on the assumption that CO_2 concentration does not exceed 400 ppm. The analysis shows that oil-based derivatives fuel will remain the dominant fuel until 2050. Beyond 2050, hydrogen becomes an economically attractive alternative for gasoline/diesel compared to liquid biofuels obtained from biomass. These conclusions have been supported in the following ways:

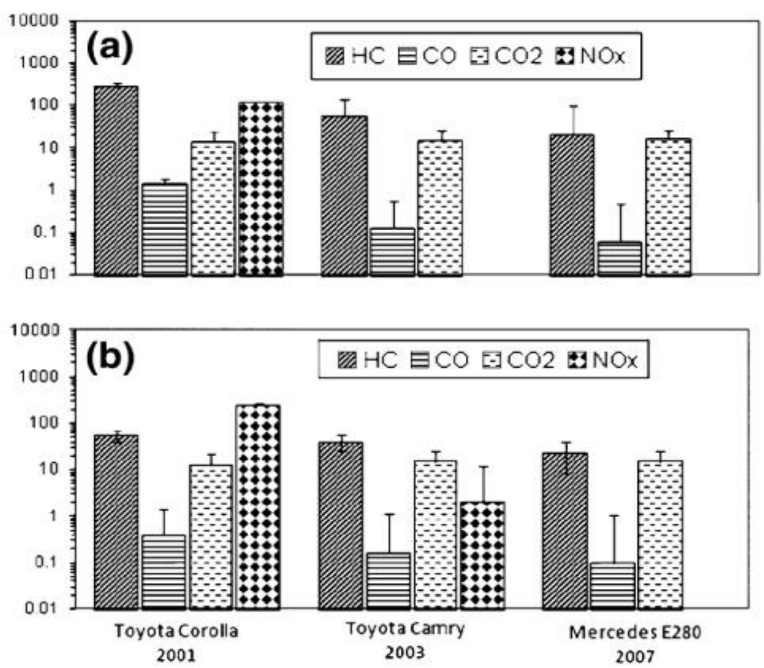
Firstly, from a physical perspective, the current crude oil and natural gas reservoirs contain less than half the amount of carbon that could be emitted during 1990-2100 to keep CO_2 concentration lower than 400 ppm. Due to CO_2 constraints, natural gas will dominate in the electrical sector while oil derivatives will be highly competitive in the transportation sector.

Secondly, the rise in gasoline price because of the Kyoto Protocol constraint is estimated at 0.04 USD/l which is lower than justifying a transition to methanol in the short run.

Finally, these results have also been supported by empirical evidence. During the 90s, when a carbon tax was deployed in Sweden (equal to 200 USD/ton C for transportation and district heat applications), the transport sector did not witness a transition to biofuels compared to district heating. This was due to the lower heat loss when converting biomass to biofuel for heat production purposes.

After 2050, there will be two options for the transportation sector, either hydrogen or liquid biofuel. The limited supply of biomass and the higher energy loss when converting it into biofuels make biofuel less competitive in the transportation sector compared to hydrogen.

However, to the author's best knowledge, very few publications can be found in the open literature that addresses the issues of CO_2 emissions from the Kuwait transport sector (Elmi and Al Rifai, 2012) (Figure 13). The rapid increase of private vehicles after the discovery of oil affects air quality, particularly in densely populated areas. This rise will accelerate the demand for the introduction of standards in fuel economy, especially in heavy vehicles.



Source: (Elmi and Al Rifai, 2012)

Figure 13. Reproducibility of pollutants emissions during driving modes

2.2 Carbon Capture Technologies

In general, CO_2 can be captured from anthropogenic activities through three leading capture technologies, post-combustion, pre-combustion, and oxy-fuel combustion. Each capture techniques have sub-categories with some reaching the commercial stage while others are still in the R&D phase (Figure 14).

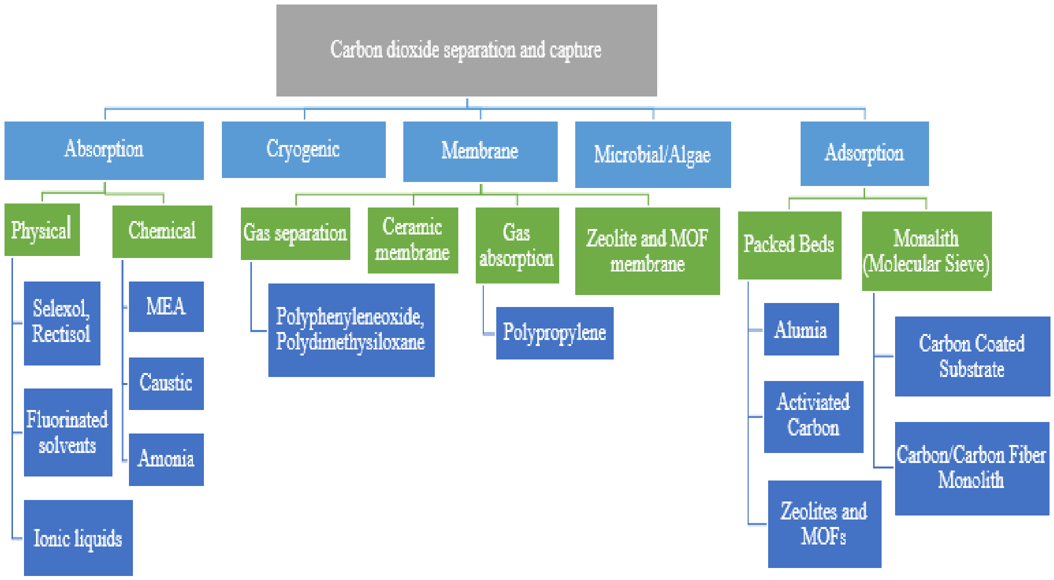


Figure 14. Carbon capture technologies adapted from (Li, et al., 2013)

2.2.1 Pre-Combustion

Pre-combustion is a form of fuel decarburization through the reaction of the fuel in gasification, partial oxidation or steam reforming process to produce syngas (Leung, et al., 2014). The syngas is composed of hydrogen and CO.

$$H_2O + CH_4 \rightarrow 3H_2 + CO \qquad (2)$$

Steam is then used in a water gas shift reaction to convert CO to CO_2 as well as produce further hydrogen.

$$H_2O + CO \rightarrow H_2 + CO_2 \qquad (3)$$

The high partial pressure and concentrated CO_2 produced from these reactions will increase the driving force for separation. The valuable hydrogen produced from these reactions could be re-used in various chemical pathways.

2.2.2 Post-Combustion

The post-combustion technique is known as the end of the pipe technique where CO_2 is eliminated from the flue gas obtained from the combustion of carbonaceous fuel (Liang, et al., 2016). It is the most mature approach that could be retrofit to any existing facilities without radical changes. The high-energy requirement used to regenerate solvents is the main drawback of large-scale deployment of the post-combustion technique (Zhang, et al., 2019).

D'Alessandro, et al. (2010) emphasized that the efficiency of the post-combustion process could be improved by replacing the solvent with lower heating adsorption ones. Improving mass transfer, reaction kinetics, in addition to increasing the concentration of adsorbent molecules, could also play a role in enhancing the post-combustion efficiency. Inhibitors are usually added to reduce corrosion formation due to the presence of oxygen in the flue gas.

2.2.3 Oxy-fuel Combustion

Oxy-fuel combustion was developed to overcome the main barriers of the post-combustion process, namely the low level of CO_2 concentration in the flue gas. In this technique, the fuel is burned in an almost pure oxygen environment, in place of air, mixed with Recycle Flue Gas (RFG), to decrease the high temperature, which gives both water and a high concentration of CO_2 (Tang and You, 2018). Ionic Transport Membrane (ITM) was developed to become an economically attractive alternative for Air Separation Unit (ASU) (Dillon, et al., 2015). Figure 15 shows a comparison between the three carbon capture technologies (Kanniche, et al., 2011).

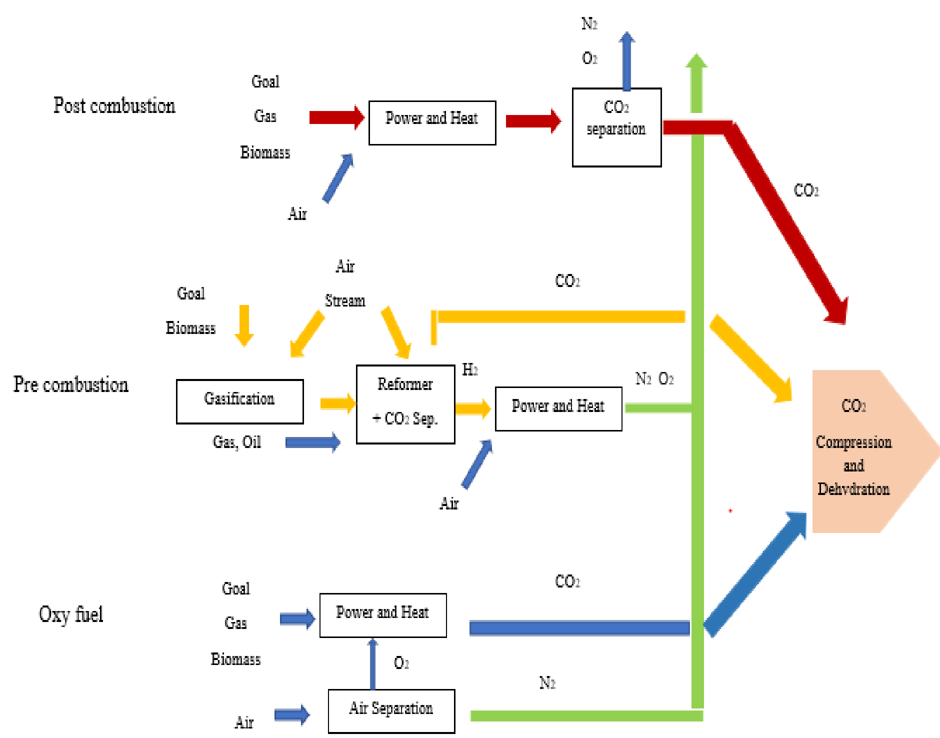


Figure 15. A comparison between the three-carbon capture process adapted from (Kanniche, et al., 2011).

2.3 Carbon Dioxide Separation Technologies

2.3.1 Chemical Absorption

Chemical absorption relies on the interaction of liquid sorbents with CO_2 in the flue gas (Herzog and Golomb, 2004). A weak bond is formed between the sorbent and CO_2 that can easily be broken by heat. The sorbent could be either organic or inorganic solvents. In comparison to the other capture techniques, chemical absorption is the most developed method for CO_2 separation (Liang, et al., 2016).

- *Organic Solvent*: organically based amines, known as aqueous alkanolamine, are the most common solvent used and are classified into primary, secondary, and tertiary amines (Wang, et al., 2011; Gunter, et al., 2005) (Figure 16). Each group varies in reaction rate, equilibrium absorption, and sensitivities to the other by-products such as SOx and NOx. Although the amines-based system has been used commercially for many years in chemical industrial processes (*e.g.* ammonia production, natural gas treatment), there is still room for improvement.

Research has focused on four pathways: 1) Increasing contact between solvent and CO_2 through modified tower packing, 2) Eliminating corrosion problems by using several types of additives, 3) Reducing the energy requirement through rising heat integration, and finally 4) Improving the regeneration processes to promote the amine-based systems. With more than 90% efficiency, Mono- Ethyl Amine (MEA) seems the most promising solvent for use in carbon capture techniques.

The demand to overcome the main challenges of using the amine-based system are the main barriers of widely deploying these sorbents. These challenges can be summarized as an amine degradation problem that will cause a solvent loss and generate volatile compounds and eliminate the equipment corrosion problem. Piperazine and anion-functionalized ionic liquid are the second generations of chemical absorption sorbents that react much faster than MEA (Leung, et al., 2014). Using piperazine in carbon capture is still in the development stage and research is needed to overcome its more significant level of volatility in comparison with MEA.

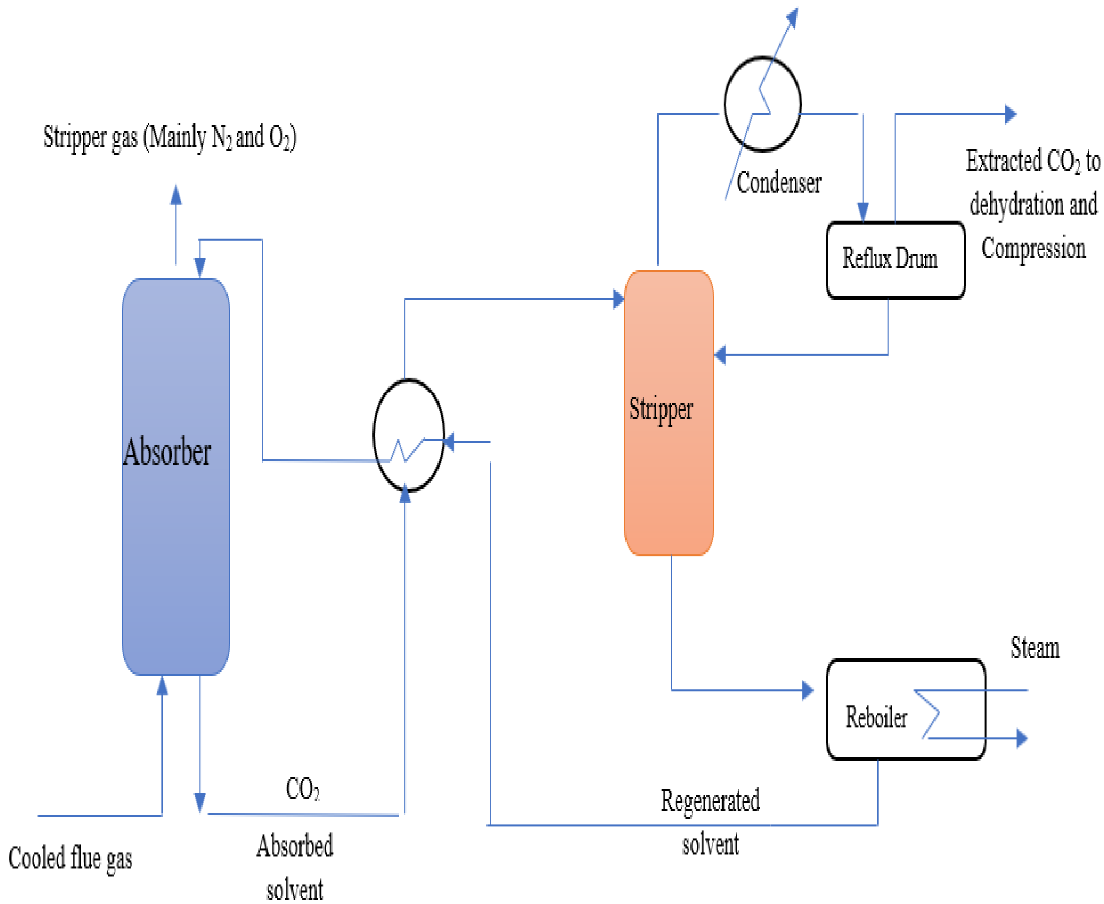


Figure 16. A typical absorption process for CO_2 capture from flue gas adapted from (Gunter, et al., 2005)

- *Inorganic Solvents:* aqueous ammonia has similar mechanisms to scrubbing with amine solvent. With lower energy demand for absorption and desorption, aqueous ammonia is among carbon capture techniques that have an enormous potential to replace the amine-based system (D'Alessandro, et al., 2010).

Figueroa, et al. (2008) indicates that the aqueous ammonia has a higher capacity for CO_2 capture, a lower degradation rate in the presence of oxygen along with an increased possibility of forming fertilizers through interaction with a pollutant (*e.g*. SO_x and NO_x). Research and Development (R&D) pathways are focused on overcoming the few concerns associated with using ammonia. These concerns include the higher volatility rate and the demand to cool the flue gas to enhance the absorption process.

2.3.2 Adsorption

A solid surface is used in this technology, instead of sorbent, to form an intermolecular force with CO_2 (Oreggioni, et al., 2015). The adsorption rate will be affected by temperature, partial pressure, surface force, and adsorbent pore size (Gunter, et al., 2005). Then Pressure Swinging Adsorption (PSA) or Temperature Swinging Adsorption (TSA) is used to recover the saturated sorbent with CO_2 (Kuramochi, et al., 2012). The most common solid adsorbents used in this technique are activated carbon, zeolites, calcium oxides, hydro-talcites and lithium zirconate (Leung, et al., 2014). Anderson and Newell (2003) illustrate that the intermolecular forces that are formed between the surface and the gases are affected by, temperature, partial pressure, surface force, adsorbent pore sizes, and the number of layers. Adsorption has an advantage due to its lower energy consummation in the regeneration process.

2.3.3 Cryogenic Separation

As the name implies, cryogenic distillation is a cooling process followed by frictional condensation to separate CO_2 from flue gas (Wilberforce, et al., 2019). Due to high-energy demand, this technique is only preferred for flue gas with more than 50% CO_2 concentration and has the potential to capture around 90-95% of CO_2 (Leung, et al., 2014).

2.3.4 Second Generation Post-Combustion Technologies

- *Gas separation membrane:* certain gases can separate from the flue gas by using the selective membrane. The membrane is usually composed of multilayers, a dense layer bonded to the dense thicker layer to provide mechanical support for the selective layer.

These layers are usually made of organic (polymeric) or inorganic (carbon, zeolite, ceramic, or metallic) substances (Lindqvist, et al., 2014).

The variation in partial pressure is the main driving force of gas permeation through this membrane. The permeability *(P)* of these gases can be defined by the function of solubility (*S*) and diffusivity (*D*).

$$P = S \times D \tag{4}$$

The high demand for flue gas compression, to create this variation in partial pressure, is the main barrier to deploying this technique on a larger scale.

- *Gas absorption membrane:* a membrane is used in this technique as a contacting device between gas flow and liquid flow (Rubin, et al., 2012). The liquid on one side of the membrane interacts with a component in the flowing gas to separate CO_2. Figure 17 illustrates the variation in the principle between gas separation and gas absorption membrane (Gunter, et al., 2005).

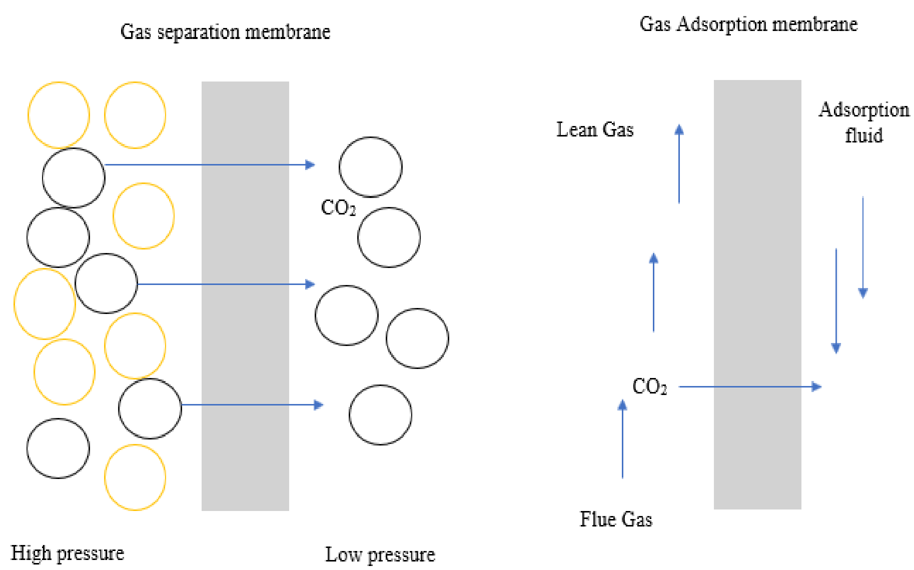


Figure 17. Principle of gas separation and gas absorption membrane adapted from (Gunter, et al., 2005)

- *Chemical-looping combustion:* this novel combustion process was developed to address the issue of high energy demand in previously discussed capturing methods. A metal oxide is used as the primary oxygen carrier rather than using pure oxygen, as utilized in oxyfuel combustion (Yan, et al., 2020). The metal oxide circulates between two interconnected fluidized bed reactors; fuel and air reactors (Figure 18). The overall stoichiometry reaction in the fuel reactor can be summarized as follows:

$$(2n+m)\ M_yO_x + C_nH_{2m} \rightarrow (2n+m)\ M_yO_{x-1} + mH_2O + nCO_2 \qquad (5)$$

The flow gas stream obtained from the complete fuel combustion is a combination of water vapor and pure CO_2 without further need for gas separation. In the air reactor, the reduced metal oxide will be re-oxidized again according to the following reaction:

$$MyO_x1 + 1/2\ O_2(air) \rightarrow M_yO_x + (air{:}\ N_2 + ureacted\ O_2) \qquad (6)$$

With minimum negative environmental impact, the stream yielded from this reactor contains only unreacted oxygen and nitrogen.

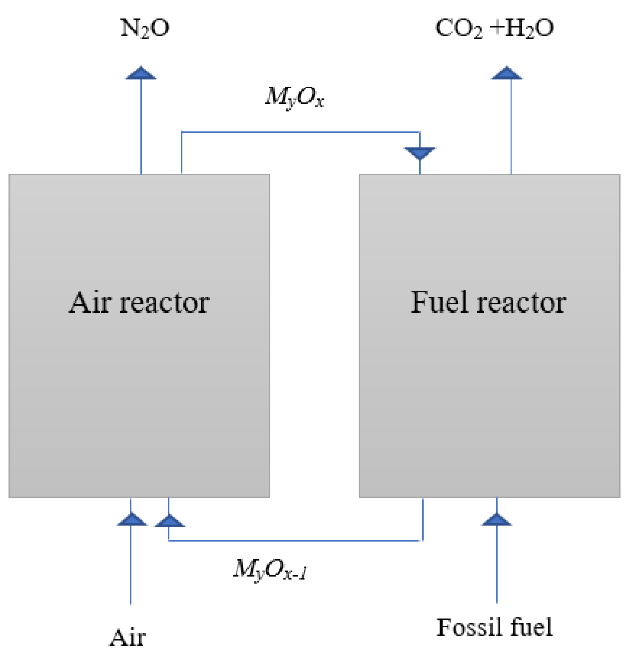


Figure 18. Schematic representation of chemical-looping combustion process adapted from (Hossain and Lasa, 2008)

The main challenge of CLC is obtaining an oxygen carrier that can maintain its reactivity over the cycle reaction.

- *Hydrate based separation:* in this innovative technology, CO_2 is separated from other gases by forming a hydrate after exposure to water under high pressure (Mondal, et al., 2012). This technology is among the most promising technologies of CO_2 separation under the R&D phase, where it has the advantage of lower energy demand (Leung, et al., 2014). The efficiency of the capture process can be increased by improving the hydrate formation rate and reducing hydrate pressure.

- *Suitability of the capture system:* each capture technology mentioned above is used in different applications due to its various limitations. Flue gas yield from most industrial systems has a low concentration of CO_2. Therefore, chemical absorption through the post-combustion system is the most suitable technique to use. Gunter, et al. (2005) clarified in Table 1 the suitability of the separation process to feed gas streams.

Table 1. Suitability of separation processes to feed gas streams

Capture Technology		CO_2 Concentration (%)	Feed Gas Pressure (MPa)	Operating Temperature (°C)	Pre-treatment
Absorption	Chemical	> 3	> 0.1	50	Required
	Physical	> 20	> 2	Low-10	Required
Adsorption	> 30	Moderate	Low to moderate	Low to moderate	Required
Cryogenic	> 90	Moderate	Low	Low	Required
Membrane	> 15	> 0.7	Feed temperature	Feed temperature	Required

Source: (Gunter, et al., 2005)

These second-generation capture technologies have been evaluated in recent years in various industrial sectors such as cement production (Lindqvist, et al., 2014; Scholes, et al., 2014; Rodríguez, et al., 2012) to upgrade these technologies from pilot stage to commercial stage.

2.4 Carbon Dioxide Utilization

Generally, the captured CO_2 can take either one of the two utilization pathways:

- Utilizing CO_2 into certain chemicals or fuels through either carboxylation or reduction avenues (Norhasyima and Mahlia, 2018) (Figure 19).
- Using CO_2 in its supercritical state without any modification reactions such as in Enhanced Oil Recovery (EOR) (Algharaib, 2013; Usman, et al., 2014; Li-ping, et al., 2015; Kwak and Kim, 2017).

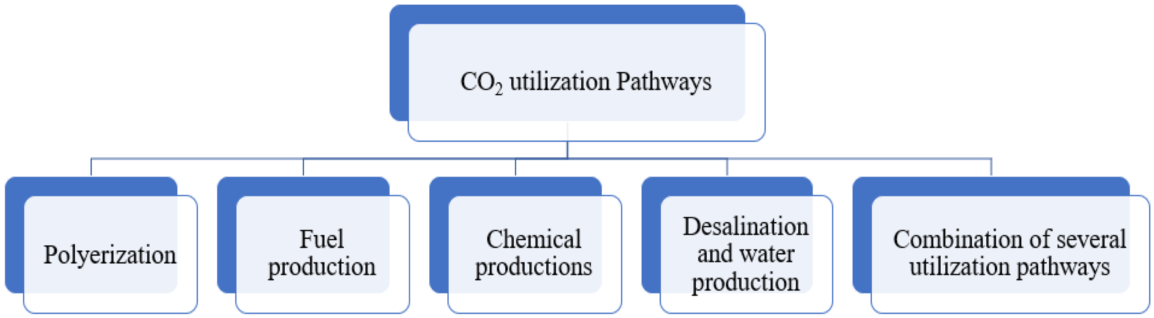
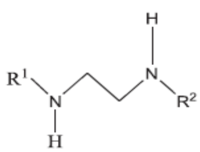
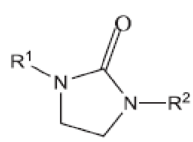


Figure 19. Carbon dioxide utilization pathways

Utilizing CO_2 in valuable petrochemical products or as fuels are several of the attractive pathways that have received global attention. In the chemical industry, CO_2 can be used as a substrate, solvent, and extracting agent. Alper and Yuksel Orhan (2017) illustrate some of the chemicals that can be produced from CO_2 and their annual global production. Urea production is among the primary consumers of CO_2 (IEA, 2013a). The scale of utilizing CO_2 in these chemicals needs to be exceptionally large to have an impact on reducing the global CO_2 emissions.



$+ CO_2 \leftrightarrow$



$+ H_2O$ (7)

- Chemistry and thermodynamic aspects of CO_2 fixation

Transformation reactions of CO_2 into other chemicals can generally be categorized into (Figure 20):

- Reactions that do not require an external input of energy. These reactions are known as carboxylation reactions where the entire CO_2 molecule is incorporated into other molecules such as urea formation.
- Reactions that need an external input of energy to produce a reduced form of CO_2 such as formaldehyde formation. This external energy could be supplied in the form of heat, electrons, or irradiation/photons.
- *C1-building block chemicals:* using CO_2 as a C1-chemical building block is the potential entry point for utilization of CO_2 in the polymer industry. It starts with the conversion of CO_2 into methanol, which can selectively oxidize into formaldehyde. Carbonates can also

form from the direct reaction of CO_2 with alcohol. Additionally, being an economic building block for polymers, CO_2 could make a significant contribution to the final product mass.

- *Catalysis relevant to CO_2 conversion:* the catalyst is an essential element in reducing the high energy barrier in CO_2 conversion. Either homogeneous, heterogeneous, or biological catalysts can be used for this purpose (Ravanchi and Sahebdelfar, 2014). Heterogeneous is the most used one, while homogeneous could also form some value-added chemicals such as carbamates. The reactions occur on transition metal center M. Heterogenous catalysts can only be used for hydrogenation reactions such as equations (8-10). These reactions play a crucial role in utilizing CO_2 in the petrochemical industry (Ravanchi and Sahebdelfar, 2014):

$$CO_2+H_2 \leftrightarrow CO+H_2O \qquad \Delta H_{298}= +41 \text{ KJ/mol} \qquad (8)$$

$$CO_2+3H_2 \leftrightarrow CH_3OH +H_2O \qquad \Delta H_{298}= -49.9 \text{ KJ/mol} \qquad (9)$$

$$CO_2+4H_2 \leftrightarrow CH_4 +2H_2O \qquad \Delta H_{298}= -113 \text{ KJ/mol} \qquad (10)$$

Electro- or photochemical reduction of CO_2 is among the intelligent pathways for the utilization process that has enormous potential for future use. Reversed fuel cells can be used for electrocatalytic reduction of CO_2 to produce oxygenates. The selectivity behavior of various aqueous solutions will vary according to electrode type.

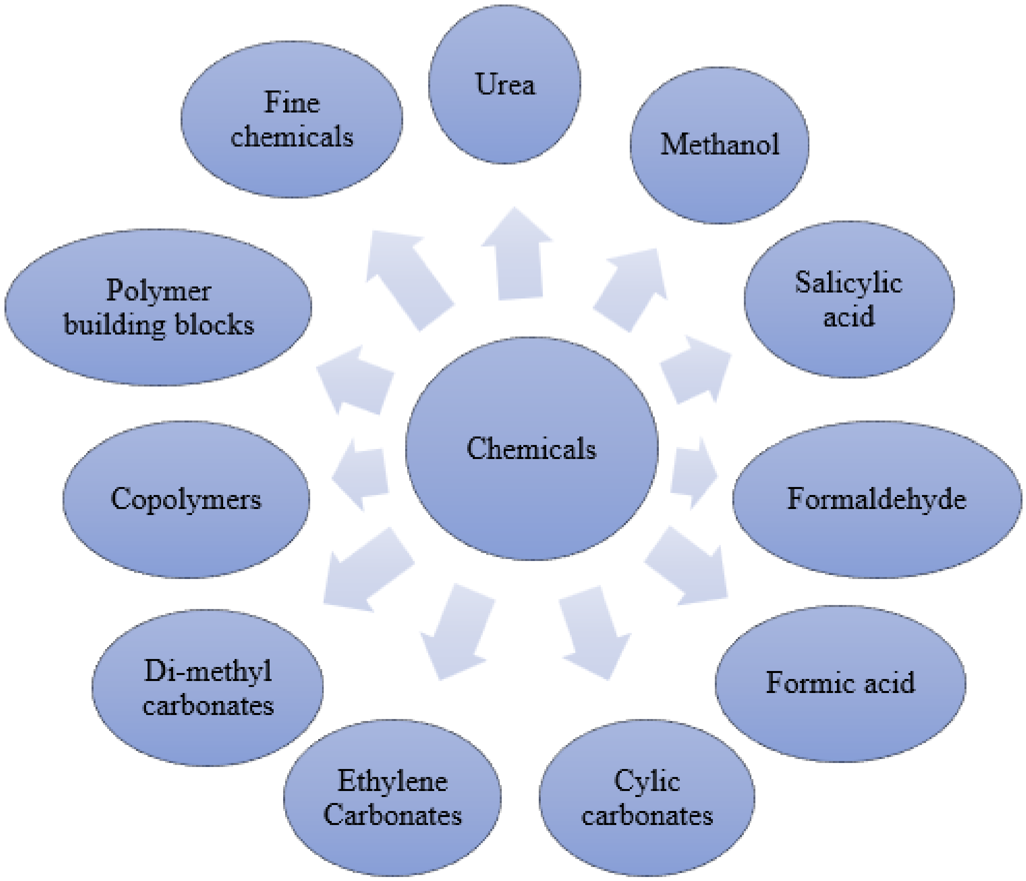


Figure 20. Some chemicals which can be produced from CO_2 adapted from (Alper and Yuksel Orhan, 2017)

- *Polymerization:* the high global demand for polymers and construction materials will provide one of the largest potential markets for captured CO_2. Only polymers that can use CO_2 as a C1-building block have a high fixation potential. Urea-formaldehyde resin (UF-resins) and melamine-formaldehyde resins (MF-resins) are two examples of macromolecules that can be constructed in a way in which CO_2 can form the entire carbon backbone of the structure. Moreover, the captured CO_2 could also have a role in polyurethane and polyoxymethylene production which could partially replace polypropylene and polyethylene (Alper and Yuksel Orhan, 2017).
- *Fuel production:* through either CO_2 hydrogenation or Dry Reforming of Methane (DRM), carbon dioxide could also be used as a building block for fuel production (Schakel, et al., 2016; Debek and Dębek, 2017) (Figure 21). Methane, methanol, syngas, and alkanes are examples of the feedstock that can be produced for this purpose. In comparison with

methane, methanol has a higher volumetric density, and it is more valuable to use as an alternative for conventional fuel. Methanol alone could contribute to eliminating 0.1% of global CO_2 emissions, where it participates in paints, plastics, combustion engines, and organic solvents industries (Al-Mamoori, et al., 2017). Renewable sources of energy (*e.g*. solar or wind energy) could be used in the hydrogenation process as a fossil fuel alternative to eliminate the associated CO_2 emissions.

Producing CO through Reverse Water-Gas-Shift (RWGS) reaction seems a more economically attractive pathway for methanol production due to the endothermic nature of the reaction. However, the demand for having an active catalyst to accelerate the reaction will remain a significant hurdle.

Quite recently, considerable attention has been given to the Dry Reforming of Methane (DRM) pathway due to its highly endothermic reaction and ability to produce high purity of syngas. The second process of the reaction, in which syngas is converted into methanol, relies on the ratio of H_2/CO that should be approximately two. In a typical DRM reaction, the ratio is not exceeding one, which raises the demand for the addition of extra hydrogen. Although it is not possible to produce methanol with this ratio, it is sufficient to yield Di-Methyl Ether (DME), which is considered a cleaner substitute for diesel.

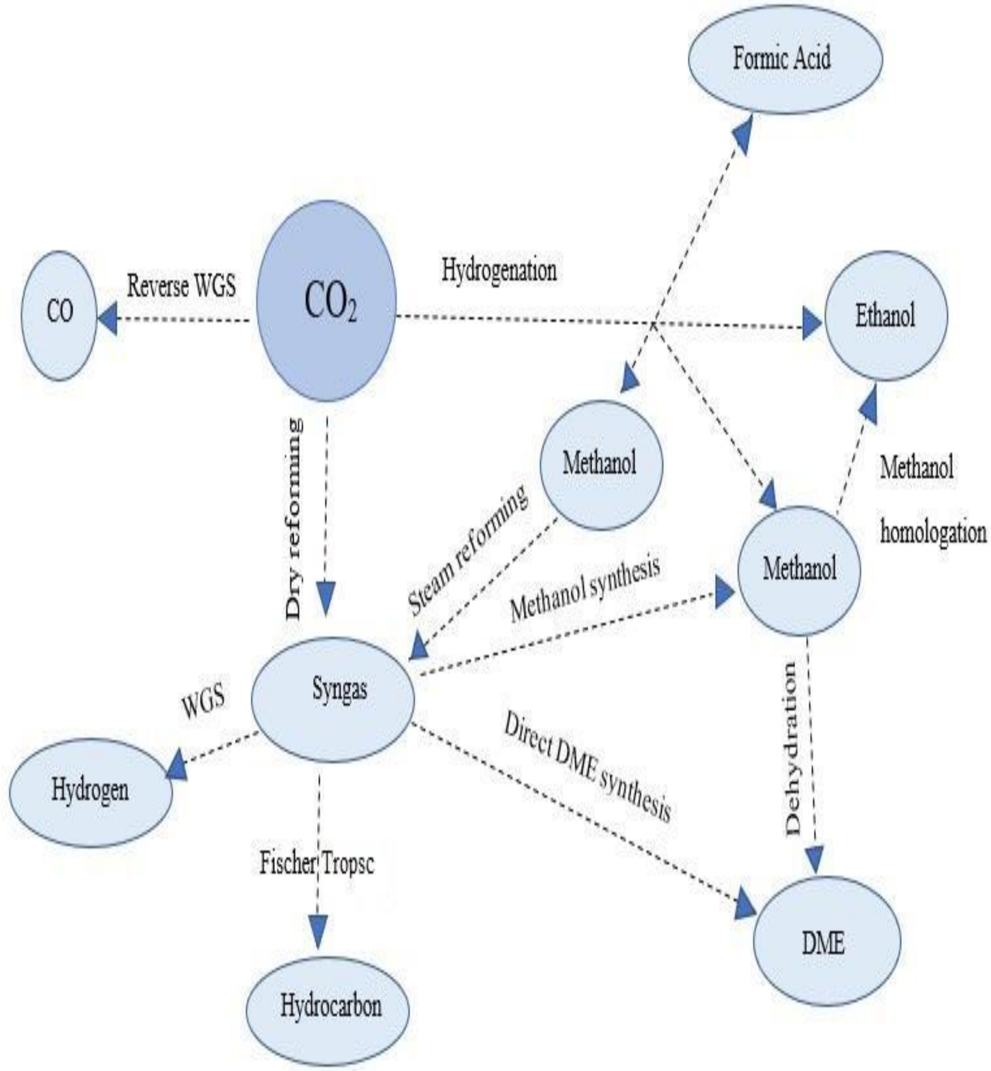


Figure 21. The main routes to convert CO_2 into fuel and fuel additives adapted from (Schakel, et al., 2016)

- *Chemical production:* a large array of fine chemicals could also synthesize from CO_2 utilization. Urea, inorganic carbonates, polyurethane, cyclic acid and crylates, polycarbonates and alkylene carbonates are some examples of these chemicals that have various applications in pharmaceutical, agrochemical, lubricant, coating, etc.

Particular attention has been given to the utilization of CO_2 in Carbon Nano Tube (CNT) production (Motiei, 2001). The process occurs at 1000 °C with the interaction of CO_2 with magnesium (Mg) to give magnesium oxide.

- *Desalination and water production:* removing Total Dissolved Solids (TDS) and transforming brine into water is another promising CO_2 utilization pathway. This process starts with mixing ammonia with seawater then exposing the mixture to CO_2. As a result, both $NaCO_2$ and NH_4Cl will form and easily settle at the bottom of the tank. Another technique used for desalination purposes is the hydrate forming approach which has the advantage of using CO_2 in both its liquid and gas phase.
- *Combination of several utilization pathways:* improving a holistic approach to overcoming limitations of each single utilization pathway could have significant beneficial impacts on achieving the target of CO_2 fixation. In this respect, Fernández-Dacosta, et al. (2018) explore the techno-economic and environmental feasibility of combining Carbon Capture and Utilization (CCU) and CCUS in the configuration of refineries. An approximate 18% reduction of CO_2 emissions, in comparison to reference configuration, has been achieved. This analysis could pave the way for closing the carbon cycle in the petrochemical industry.

2.5 Long Term Sequestration of CO_2

For several years, a significant global effort has been devoted to investigating the potential of using CO_2 in Enhanced Oil Recovery (CO_2-EOR). Carbon dioxide in Enhanced Oil Recovery (CO_2-EOR) is commonly used after primary and secondary conventional approaches in order to produce an additional 5-20% of the Original Oil In Place (OOIP) (Kwak and Kim, 2017).

Beyond its potential to increase crude oil production, CO_2-EOR adds value to eliminate the anthropogenic GHGs through permanent sequestration of CO_2 in these reservoirs. For this reason, CO_2-EOR has been widely investigated in a vast amount of literature. Van Bergen, et al. (2004), and Teir, et al. (2010) analyzed the worldwide potential of CO_2-EOR by using Geographical Information System (GIS) to form site-specific information. This approach is useful when identifying early opportunities for CO_2-EOR and CO_2 sequestration. In the Middle East, Jaju, et al. (2016) presented a comprehensive review of techno-stratigraphic and paleoclimatic evaluations in the Kingdom of Saudi Arabia (KSA) to identify the optimal reservoir for CO_2-EOR and long-term storage of CO_2. The research identified the geographical districts of hydrocarbon prolific and non-prolific sectors in KSA. The lithological variation between the two sectors was explained by tectonic inversion that occurred in the Arabian Arch. Understanding the interplay of the factors behind these variations such as paleo-geographic configuration and structural inversions can form a knowledge base for the State of Kuwait since both countries are located on an Arabian plate and have undergone similar geographical development (Carman, 1996; Al-Sulaimi and Al-Ruwaih, 2004; Al-Sarawi, et al., 2006; Mohammad, 2008; Al-Awadhi and AlShuaibi, 2012).

Li-ping, et al. (2015) assessed the geographical and geological conditions of 21 oil fields around Yulin City in China for CO_2-EOR and long sequestration purposes. Based on this data, eight of the oilfields were suitable for miscible flooding while nine were for immiscible. Miscible flooding is one of the EOR methods that has been successfully applied in many regions in the world, such as the United States. Likewise, Kuwait has started to evaluate the CO_2 miscible flooding on west reservoirs. After meeting the screening criteria, core samples from each reservoir have been collected to measure the Minimum Miscibility Pressure (MMP) and identify the optimum injection scenarios. The analysis aimed to provide a valuable database to extend miscible flooding to the other reservoirs in the state (Alajmi, et al., 2015).

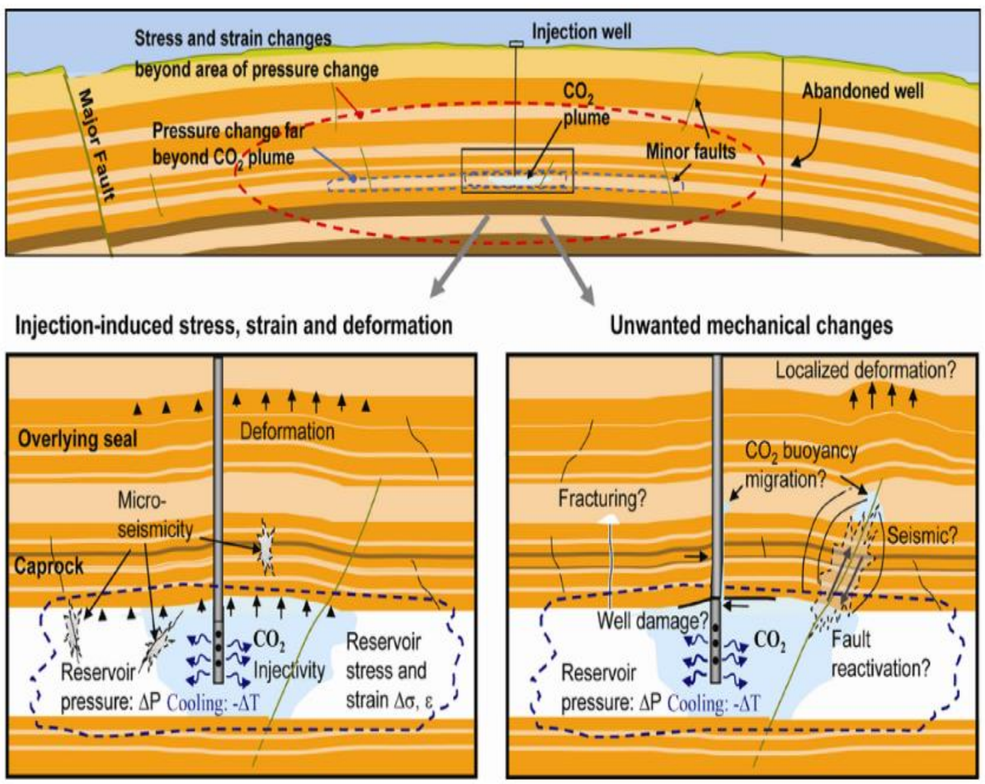
Despite all the economic advantages of CO_2-EOR, there are some operational and technical risks associated with this process, such as CO_2 burning through production wells due to its low viscosity. Because of these, most CO_2-EOR projects inject CO_2 with water in a water-alternating-gas (WAG) approach (Arnaut, et al., 2021).

A set of comprehensive simulation and monitoring systems were developed to evaluate the sequestration of CO_2 in the reservoir. In the Shaanxi Province of China, Ma, et al. (2013) designed a system to monitor the CO_2 behavior by detecting the geophysical, geological, and environmental surface variations inside and around the reservoir. In contrast, Dai, et al. (2017) conducted a statistical-based simulation known as Monte Carlo (MC) in the Morrow reservoir to evaluate environmental and economic risks.

Another viable option to reduce or slow the build-up of CO_2 concentration in the atmosphere is storing CO_2 in a saline aquifer. The theoretical capacity of saline aquifer was estimated to be around 10,1000 Gt CO_2 while for depleted oil and gas reservoirs it varies from 675 to 900 Gt CO_2 (Anchliya, 2009). These two formations were able to store hundreds of years' worth of CO_2 emissions. Replacing more viscous brine with less viscous CO_2 causes a series of physical and chemical alterations that could affect the permeability and porosity of the target reservoirs due to rock mineral dissolution (Izgec, et al., 2008). The low viscous CO_2 raises another concern regarding the leakage of CO_2 leakage aquifer faults (Kumar, et al., 2005).

Because of these, a large body of research has been undertaken to better understand the migration pathways of CO_2 inside the reservoir. Kumar, et al. (2005) simulated the prototypical CO_2 sequestration project for up to 10^5 years to analyses the impacts of several parameters including the average permeability, residual gas saturation, aquifer dip angle, and salinity. Similarly, Nordbotten, et al. (2005) used a numerical simulation to evaluate the maximum spatial extent of CO_2 plume inside the reservoirs. Flett, et al. (2007) and Ghanbari, et al. (2006) affirmed the role of reservoir heterogeneity on the CO_2 pathway. Reservoirs with higher shale content show a reduction in vertical flow in comparison to lateral flow.

Additionally, Birkholzer, et al. (2015) demonstrated that unwanted pressure impacts can cause leakage problems and geochemical damage (Figure 22). The analysis provides some engineering solutions to overcome this issue, such as brine extraction and, in some cases, re-injection.

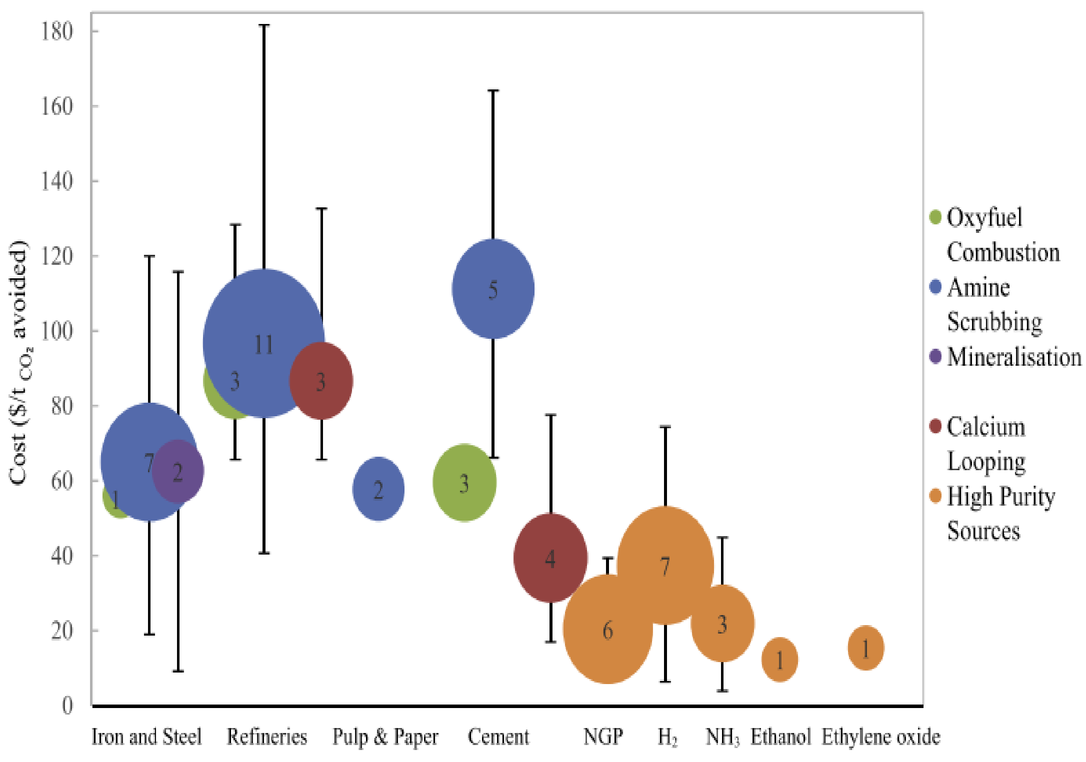


Source: (Birkholzer, et al., 2015)

Figure 22. Geomechanically process and key technical issues associated with CCUS in deep saline formations

2.6 Carbon Capture, Utilization and Storage (CCUS) Cost

As previously discussed, cost is a key barrier to the widescale deployment of CCUS technologies. All recent R&D activities undertaken in this area have been focused on developing lower-cost technologies (Figure 23). Various industrial, government, and non-government organizations are interested in CCUS economic analyses and most of them are CO_2 producers. A Special Report on Carbon Dioxide Capture and Storage (SRCCS) prepared by the Intergovernmental Panel on Climate Change in 2005 assesses the recent changes in CCUS systems and costs across the full value chain. The following section briefly describes the different levels of techno-economic analyses of carbon capture technologies.



Source: (Leeson, et al., 2017)

Figure 23. Mean cost of CCUS technologies on different industries

The main uncertainties regarding CCUS cost estimation of natural gas power plants were analyzed using both sensitivity and probabilistic analyses. It concludes that the rise in Levelized Cost of Electricity (LCoE) is 20-32 USD/ MWh for constant 2007 and it reaches 23-39 USD/ MWh when deploying CCUS (Rubin and Zhai, 2012). One technical option for reducing the additional cost of electricity due to deploying CCUS techniques is turning off the energy used for the capture process during peak time (Haines and Davison, 2009). Correspondingly, the feasibility of oxyfuel combustion in the refinery power plant had also been illustrated in (Escudero, et al., 2016). The capture technique could be technically and economically feasible with a payback period of between 9 and 11 years and an Internal Rate of Return (IRR) value of around 7%.

In downstream petroleum processes, 40% of overall refinery emissions are yielded from dispersed sources (Van Straelen, et al., 2010). The cost of capturing CO_2 from these sources is four times higher than the hydrogen production unit (Van Straelen, et al., 2010). Meanwhile, the main technical and economic barriers of retrofitting an FCC unit with amine absorption and oxy-fire technique is illustrated in de Mello, et al. (2009) and, Digne and Gomez (2014). Based on the result, oxy-fire technique could eliminate 45% of CO_2 emissions in comparison to amine absorption.

Correspondingly, Li, et al. (2013) have proposed the techno-economic analysis of using amine scrubbing in the calcination process and oxyfuel partial capture in a precalciner with recycled O_2/CO_2. The cost of CO_2 avoided, in this case, was estimated to be 60 USD/ t CO_2 for post-combustion with chemical absorption.

In light of global interest in promoting a CCUS strategy in the iron sector (Cormos, 2016; Quader, et al., 2016; Tian, et al., 2016; Choi, and Strømman, 2013), the effectiveness of using MEA solvent absorption in steelmaking facilities was proposed by Ho, et al. (2011). The analysis covered both integrated steel mills and scarp mini mills. The annual cost of CO_2 avoided was around 250 USD per t in the mini mill in comparison to 77 USD to 100 USD per t avoided in the integrated steel mill. This value was reduced to 35 USD / t CO_2 through employing Methyl-Di-Ethanol-Amine (MDEA) (Farla, et al., 1995). Another analysis shows that 35 USD / t CO_2 is an exaggerated value when both shift reactor and Selexol had not been taken into consideration, in addition to neglecting the secondary benefit of CO_2 removal (fuel gas upgrading). According to the selected iron production pathway, this cost could reduce to 10.3-18.8 USD/ t CO_2 (Gielen, 2003).

Considering rapid development in CCUS technologies, the cost of CCUS will significantly reduce, especially when second-generation CCUS reaches the commercial stage. The selected cost model for the state of Kuwait should be based on a regional case evaluation under various conditions, especially for the power plants where the capture process could be turned off during the peak load.

In conclusion, CCUS has received global attention as an effective solution to stabilize the rapid rise in CO_2 emissions. Up to date, only three separations technologies have reached the commercial stage, namely post-combustion using amine solvents, oxy-combustion, and calcium looping. Additionally, both adsorption by using zeolites and membrane-based separation have become popular research topics to upgrade them from pilot to commercial stage. The sites, location, and characteristics of the local storage reservoirs will determine the rate of capture, as well as the demand of the pipeline network. Using CO_2 in EOR is the most promising utilization pathway that would be able to recover some of the capture cost. It can be observed that the stage of deployment of CCUS varies between Western and Middle East countries. In Kuwait and other GCC countries, the early opportunity for a CCUS mitigation strategy exists mainly because of their extensive knowledge of the oil and gas industry. The future deployment will depend on current investment in this new technology. Because of this, some GCC countries, such as Saudi Arabia, have started the R&D phase, where various institutions were engaged in research methods to overcome the main technical barriers of transferring this technology.

Chapter 3: Methodology

To support the goal of emissions reduction, as set by the Kuwait government and other stakeholders and reported in Chapter 1, a conceptual framework was designed and established to undertake this analysis, as illustrated in Figure 24. Kuwaiti industrial sectors, key players, including leading industrial organisations, which are involved in the carbon emissions process were identified during the scope definition and included organisations which produce significant CO_2 emissions. Other issues identified during the scope definition included potential CCUS alternatives, barriers, challenges, and costs incurred in deploying relevant technologies. Data required for the study were collated from primary and secondary sources including local leading industrial organizations and published literature. The data was checked and analysed in terms of relevance, completeness and reliability to ensure accuracy and quality. The study was completed, conclusions were drawn from the key findings, and recommendations were made for future studies.

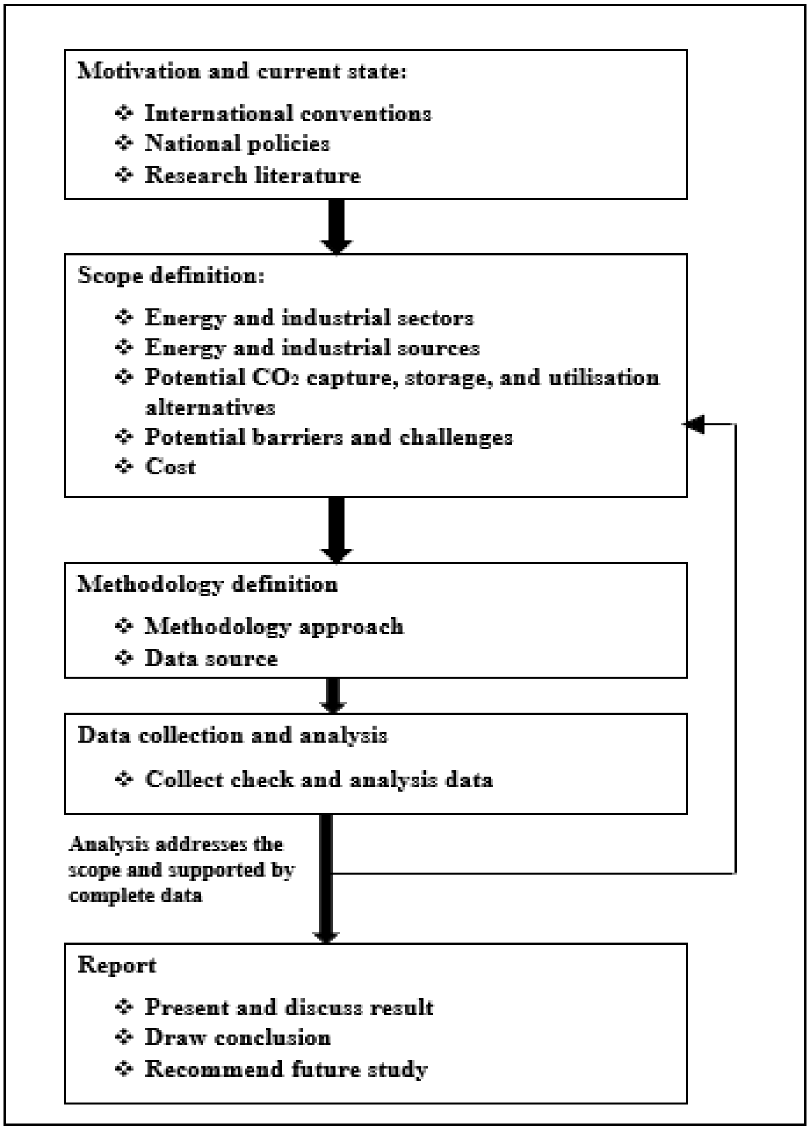


Figure 24. Conceptual framework

3.1 Development of the first carbon atlas State of Kuwait

The carbon atlas presented in this body of work is a means to understand, study and thoroughly document the sources of CO_2 emission in Kuwait using a geographical and sector-based analysis. The carbon atlas of the State of Kuwait is a scientific database developed to explore and visualize the major CO_2 emission sources yielded from human activities. Assessment and quantification methods in this atlas included the following:

- Identifying the major sectors that are responsible for national CO_2 emissions.
- Gathering data and processing information from local and international institutes.
- Identifying the CO_2 Emission Factor (EF) for each process.

- Calculating CO_2 emitted from these processes and estimating the emissions in 5, 10, and 15 years.

Therefore, and based on the above method, any process using Kuwaiti products, for example, gasoline, which ultimately releases CO_2 outside Kuwait are not considered to be Kuwaiti emissions. This assumption was made to ensure a clearly defined boundary for the state to distinguish and validate the results obtained, and particularly for making comparisons with previous results and approaches undertaken by some sectors. However, to the best of the author's knowledge, there has been no previous attempt to develop a carbon atlas across the entire state encompassing all sectors and geographical locations. The work presented in this study can therefore lead to the development of environmental strategic plans for the entire country based on an energy analysis and updated data.

Since the Kuwaiti economy is heavily reliant upon the petroleum industry, this atlas separates the upstream and downstream petroleum activities which take place in the state, in addition to the petrochemical activities. Each of the petroleum activities, outlined in Section 4.2, were considered separately. Other sectors that are globally recognized for their high carbon footprint had also been considered, i.e., cement, iron, steel, power plants, buildings, and transportation. To aggregate data from these sectors, both "top-down" and "bottom-up" approaches were used. In the top-down inventories, the data were obtained from national, and international institutes using their databases. The bottom-up approach, by comparison, relies on data from local end-users (*e.g.* local companies, industrial inventories, etc.).

After obtaining the required data, EFs for these processes were acquired from open literature and analyzed. Several internationally recognized agencies estimate EFs for various industries with the most well-known including the Intergovernmental Panel on Climate Change (IPCC) and the United States Environmental Protection Agency (EPA). The final concept of this atlas is aggregating the CO_2 emissions from these sectors and comparing the final carbon footprint of Kuwait with the values published by international agencies.

3.2 Strategic Contexts for Carbon Capture, Utilization, and Storage (CCUS) in State of Kuwait

This section aims to evaluate the options for mitigating Kuwaiti industrial CO_2 emissions. Two research objectives were defined: (1) to identify the most appropriate CO_2 capture, utilization, and storage alternatives for the key industrial sectors in Kuwait, taking account of the current state of investment and challenges of deployment; and (2) to investigate the costs of CO_2 capture for individual industrial sectors.

The first objective:

The first objective aims to provide a holistic review of the state of the art of CCUS technologies across the energy and industrial sectors. This helps to shape stakeholder perceptions about CCUS technologies by highlighting the short- and long-term benefits alongside the associated risks. The analysis considers six assessment dimensions (Figure 25), each dimension is undertaken using specific methods. The analysis is based on the results of the literature review and interviews.

For the literature review, the digital libraries were used to search for the recent scientific published articles about CCUS technologies. The research was mainly focused on the time frame from 2015 until 2021 to gain consistent insights into the progress achieved in CCUS research. In total, the review covered more than 140 articles which describe all techno-economic prospects in various sectors.

Both qualitative and quantitative surveys methods were conducted, and these were the focus group discussion and the Information- Choice Questionnaire (ICQ), respectively. The approaches were proven to provide higher quality opinions and are consistent and stable over time (Dancker, et al., 2011). The methods relied on firstly educating people about CCUS so that they had informed opinions rather than uninformed opinions.

The idea of the focus group is to provide the stakeholders with introductory information about CCUS and lead the discussion within defined constraints about the potential, risks, and utilizations. The advantage of these discussions includes the opportunity to clarify any questions and probe any vague responses. It allows the participants to explain their perspectives in their own words rather than choose from certain responses. The data obtained from this approach are usually deeper and richer in information than individual interviews (Gundumogula, 2021).

The interviews started with identifying the stakeholders affecting CCUS decisions and mapping them into groups based on their working institutions. There were 74 participants from the major industries and representatives of Ministry of Electricity and Water (MEW). The interviewees were selected by searching the state level database and the number increased through recommendations from the first group of participants. The discussion protocol was designed to allow each participant to share their organization's perspective on how CCUS could be deployed in their facilities which gives depth, nuance, and variety to the discussion. The discussions lasted for 120 (median) minutes.

The first two discussions were conducted in April 2017 with Kuwait National Petroleum Company (KNPC) and Kuwait Oil Company (KOC) experts in light of a cooperation plan to capture CO_2 from refineries to use in Enhanced Oil Recovery (EOR).

Another five discussion groups were held with representatives of the Ministry of Electricity and Water (MEW), Kuwait cement, Kuwait steel, Equate, and Kuwait Oxygen companies. The discussions were mainly based on a questionnaire containing seven sections (Appendix B):

1- Basic information.
2- The carbon footprint.
3- Carbon dioxide abatement practices.
4- Applicability of carbon capture technologies.
5- Cost.
6- The risk associated with CCUS technologies.
7- Utilization pathways.

These discussions were aimed to narrow the knowledge gap with respect to site-specific factors such as spatial and operation constraints on the efficiency of CCUS technologies. All the questions were reviewed to ensure they addressed the study objectives. The three primary commercially available capture technologies were recommended for this analysis: post-combustion, oxy-fuel combustion, and pre-combustion (Section 2.2). The discussions were supported by the facilities layouts to explain the associated technical issues with deploying CCUS technologies. Appendices (C-J) show the layouts obtained from these discussion groups.

For companies which did not participate in a focus group session, the ICQ was sent by email. The ICQ is the most elaborate form of survey to acquire information about individual perspectives of CCUS. Google Forms were used to design the ICQ. The questions were sequenced in a logical order starting with basic information about the facility and ending with possible utilization pathways for the captured CO_2. It was designed to take less than 30 min to complete which was an acceptable period for the online questionnaire (Bird, 2009). There were 18 questions used to evaluate the seven assessment sections. Each section started with a brief explanation of the measured items. All the items are measured by using a short answer or multiple choices.

The companies were selected using recommendations from the Public Authority of Industry (PAI) based on their production pathways. The aim was to send out 200 questionnaires to cover all the possible industries. However, some responses were excluded due to their very low level of knowledge about CCUS giving a final total of 137 responses.

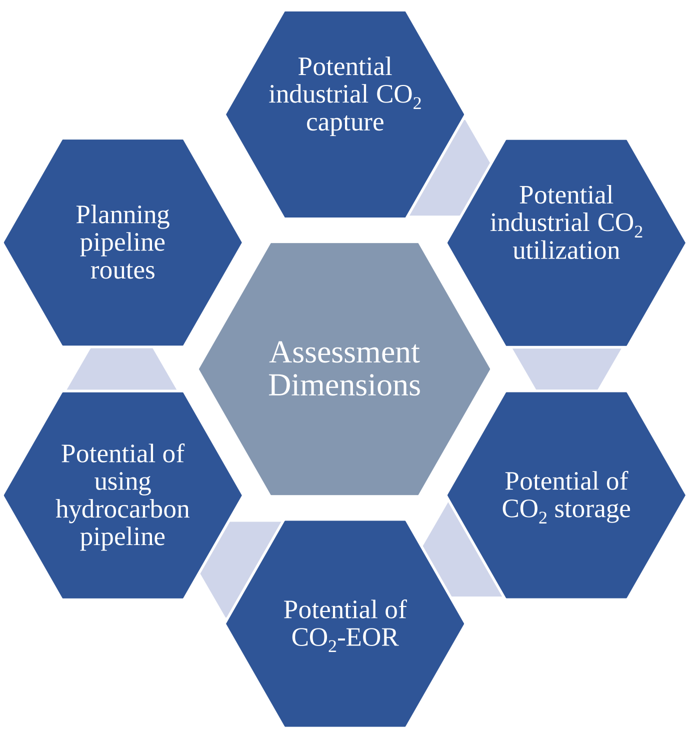


Figure 25. The six assessment dimensions covered in the analysis

Second objective

The second objective covered an economic assessment of CCUS technology. A comprehensive analysis builds upon the first section, where the cost was calculated based on the intensity of CO_2 emitted from each sector in the country. The data was taken from both existing studies and expert interviews. All the cost figures were converted to USD using 2018 as the base year to illustrate the impact of inflation. Then the latest version of Microsoft Office Excel 365 was used to host the input data, emissions intensity and estimate the capture cost for each sector. The Marginal Abatement Cost (MAC) curve was developed through both Java and Adobe Photoshop CC 2017 to demonstrate the relationship between the intensity of CO_2 emitted with the capture cost.

Chapter 4: Development of the First Carbon Atlas of the State of Kuwait

4.1 Introduction

According to a World Bank Data report (WBR, 2018), the carbon footprint of the state of Kuwait is 91.03 Million metric tons per year (Mt/y). The World Bank estimates its data by using the local consumption of fossil fuels in each country as an indicator of energy emissions. Emissions associated with cement manufacturing are taken as an indicator of non-energy carbon emissions. Similarly, the International Energy Agency (IEA, 2010b), declared that the carbon footprint of Kuwait from fuel consumption was 69 Mt in 2010. This approach is a pragmatic way of estimating the emissions levels from multiple states using a "top-down" methodology.

However, in order for each state (or country) to plan the necessary process of decarburization, a more comprehensive or "bottom-up" approach is required (Freeman, 2015). Therefore, it is essential to have a comprehensive study that details all carbon emission sources in a country to be able to address the gap in energy planning for the future. This is the primary topic of research dealt with by this thesis, where a carbon Atlas is presented for the state of Kuwait. This atlas identifies the main carbon sources and volume of emissions to be able to determine the most optimal routes of carbon usage and reduction. The development of this atlas is the key focus of this chapter. In addition, this chapter also presents a guide to the assessment of various carbon emissions industries that can also be applied to a number of countries and cities worldwide.

4.2 Petroleum Industry and Related Processes

4.2.1 Crude oil upstream processes and activities

In the oil and gas sector, upstream processes are usually known as Exploration and Production (E&P) processes (Figure 26). Several factors play a vital role in CO_2 emissions during upstream processes, including the age of the oil field, gas-to-oil ratio, reservoir depth, pressure, and viscosity.

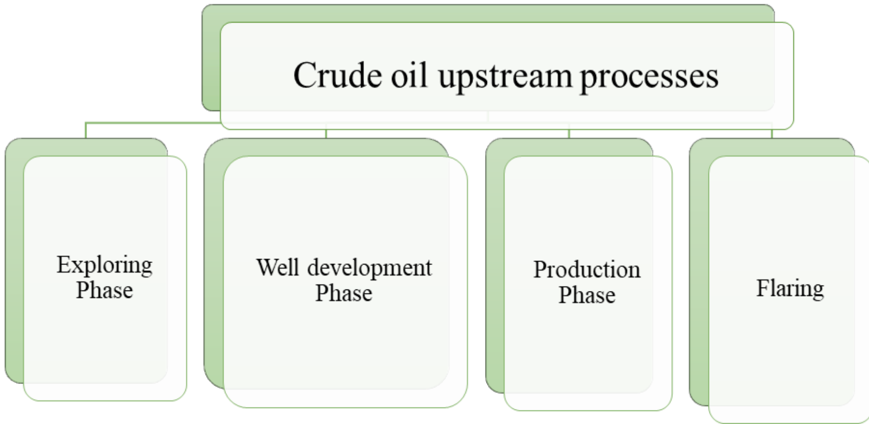


Figure 26. Crude oil upstream processes

Exploring phase: as an initial step in the exploring processes, preliminary assessment of the suspected area is conducted and includes a review of geological maps, and aerial photographs, and a geological assessment is conducted. If this assessment produces a positive result, then the exploring process moves into the second stage, which can be sub-divided into non-intrusive and intrusive surveys.

Different non-intrusive survey approaches, namely magnetic, gravimetric, and seismic, are used to explore the potential of the presence of an adequate amount of crude oil and natural gas. Carbon dioxide emissions will vary depending on the selected technique.

The real features of the reserves can only be identified using intrusive surveys (exploration drilling). The location of exploration drilling is carefully selected based upon the geological formation, to eliminate environment destruction. However, total CO_2 emissions during the exploring phase are minimal compared to the other stages.

Well development phase: during this process, CO_2 is produced from three main sources; combustion of fossil fuel in trucks in the clearing phase, building roads and from rigs during rigging up, drilling, and rigging down.

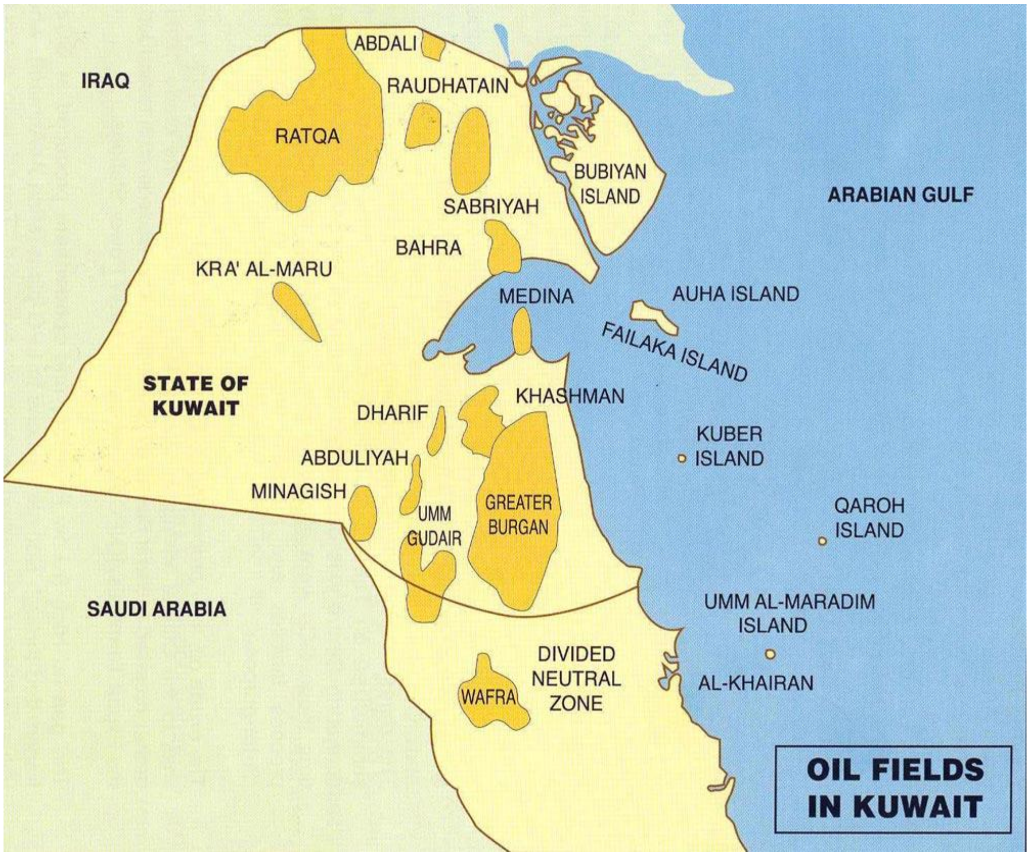
Production phase: the main source of CO_2 during primary production is the combustion of fossil fuel in compressor equipment. Usually, no more than 15% of hydrocarbon is recovered during this process and, because of this, secondary and tertiary enhancements are often employed.

Steam and pressurized gas are used as secondary enhancements to create pressure gradients within the reservoir, which produces an additional 30% of hydrocarbons. Another 30% can be obtained from tertiary enhancements by using substances (*e.g.* surfactants) (Green and Willhite, 1998). During enhancement processes, CO_2 results from two main sources; combustion of fossil fuel from injected equipment and fugitive CO_2 in tertiary enhancements when CO_2 was used as a recovery substance.

Additionally, site facilities also participate in emitting CO_2, especially in the separating and dehydrating processes in Gathering Centers (GCs), where crude oil goes through a multi-stage stabilization process to separate it from gas and water. In this case, the CO_2 is emitted as fugitive emissions from separation equipment and, as direct emissions from dehydrators. Furthermore, wastewater obtained from different processes is another source of CO_2.

In Kuwait, three major oil fields areas are responsible for the production of three million barrels per day (bpd) of crude oil. The bulk of the production occurs in the Southeast in the Greater Burgan area. It is recognized as the second-largest oil field in the world and alone is responsible for the production of 1.6 million (bpd). It consists of Burgan, Magwa, and Ahmadi oil fields with 14 GCs and two Booster Stations (BS). In the west of Kuwait, there are Minagish and Umm Gudair fields with a production capacity of 60,000 bpd each in addition to 4 GCs and two booster stations. Steam injection is already being used in the Minagish oil field to enhance oil recovery.

Finally, within the north area, where there are many oilfields, the main ones are Raudatin and Sabiriyah with 250,000 bpd, and 160,000 bpd production capacity, respectively. Kuwait also produces 300,000 bpd from The Partitioned Neutral Zone (PNZ) between Kuwait and Saudi Arabia. Figure 27 shows the location of Kuwait oilfields and the neutral zone.



Source: (Arabian gazette, 2015)

Figure 27. Location of Kuwait oilfields

Flaring is the controlled burning of waste gases obtained from different processes that cannot be economically utilized. One of the main advantages of the flaring system over other combustion units (*e.g.* heater) is its unique ability to deal with varying flow rates and composition of waste gases.

More than 95% of these waste gases are composed of natural gas, ethylene, propylene, butadiene, and butane. Flaring is the largest sole source of CO_2 emissions from all upstream processes. Carbon dioxide is a direct product obtained from the combustion of hydrocarbons where each mole of carbon converts to one mole of CO_2, under a complete combustion process. When incomplete combustion occurs, each mole of carbon will produce one mole of carbon monoxide.

According to the Kuwait Oil Company (KOC) database, the flaring process occurred at all oilfields and the CO_2 emitted rose from 0.408 Mt in 2011 to 0.48 Mt in 2015. This rise in CO_2

emitted occurred despite efforts to minimize the percentage of gas flaring to less 1% (EPA, 2016).

According to the Ministry of Oil database (MO, 2016), the local consumption of crude oil in the oil and gas production sector is 15.1 million barrels. The EF for upstream processes in Kuwait is equal to 120.45 kg CO_2e/ ton of oil equivalent (NETL, 2008), which makes the total anticipated CO_2 emissions equal to 0.255 Mt CO_2/y. The calculation of CO_2 emissions considers all associated burdens of the drilling and exploration activities in the country. It also takes into account oil production industries which utilize heavy oil.

4.2.2 Petroleum downstream processes

The downstream process includes all refining operations of crude oil in refineries and ends with the distribution of petroleum derivatives. Kuwait National Petroleum Company (KNPC) owns and operates all downstream petroleum activities in Kuwait.

Refineries are ranked as the third stationary source of CO_2 emissions after power plants and the cement industry (Van Straelen, et al., 2010). In a refinery, crude oil is processed through a series of chemical and physical processes to yield higher-value products. During these processes, CO_2 is emitted from various units, either from specific point sources (*e.g.* stack), or as fugitive emissions (*e.g.* process leakage). These emissions are closely related to the presence of residue upgrading schemes. These schemes can be classified into two categories: hydrogen addition and carbon rejection schemes (Stockle and Bullen, 2008).

Kuwait processes almost one million barrels of crude oil per day (bpd) through three refineries, Mina Abdullah (MAB) with a capacity of 270,000 bpd, Mina Al-Shuiba (SHU) with a capacity of 200,000 bpd and finally Mina Al-Ahmadi (MAA) with the largest capacity of 466,000 bpd. All three refineries are in short distance from each other, along the southern edge of Kuwait City.

Kuwait refineries have been retrofitted multiple times to meet the world's stringent environmental regulations for refineries products (*e.g.* sulfur present in diesel should not exceed 50 ppm). For this reason, all three refineries in Kuwait are complex refineries which include both thermal and catalytic cracking units. Kuwait's refining capacity increased to reach 1.4 million barrels per day (bpd), from 936,000 bpd, after completion of both the Clean Fuel Project (CFP) and the New Refinery Project (NRP).

Hydrogen production unit: the industrial demand for hydrogen, from both the chemical and refinery industry, has increased in recent years. The hydro-treating process is the backbone of any complex refinery and is where sulfur and nitrogen compounds are removed using hydrogen. Furthermore, this process avoids catalyst poisoning in the downstream processes.

In refineries, hydrogen is obtained from two main pathways, either as a by-product from other processes (*e.g.* catalytic reformer) or manufactured (*e.g*. Steam Methane Reforming, SMR) (Lindsay, et al., 2009). Reforming of hydrocarbon by steam is the main commercial pathway, with SMR used in 95% of refineries (Wheeler and Collodi, 2009). In SMR, three reversible reactions take place to form hydrogen:

$$CH_4+H_2O \rightarrow CO+3H_2 \qquad \Delta H_{298}=+206 \text{ kJ/mol} \qquad (11)$$

$$CO+H_2O \rightarrow CO_2+H_2 \qquad \Delta H_{298}= -41 \text{ kJ/mol} \qquad (12)$$

$$CH_4+2H_2O \rightarrow CO_2+4H_2 \qquad \Delta H_{298}=+165 \text{kJ/mol} \qquad (13)$$

Stockle and Bullen (2008) have estimated that for each one metric ton of hydrogen produced, ten metric tons of CO_2 is emitted to the atmosphere.

A Hydrogen Production (HP) unit exists in all Kuwait refineries. Starting with the most complex one: MAA has four SMR units, each with 49.5 Million Standard Cubic Feet per Day (MMSCFD) capacity and is able to produce 97% hydrogen. Each unit has utilization capacity ranges between 55-76%. Next is MAB with four HP units. Three of them have identical capacity, which is 55 MMSCFD, with the final older unit having a capacity of 39.5 MMSCFD. Utilization capacity of these units is between 53-73%. The final one is SHU with the lowest capacity of 74 MMSCFD from three SMR units. These three units can produce hydrogen with 95% purity with a utilization capacity of between 58-69%.

Al-Salem (2015) estimates CO_2 emissions from HP by following the equation below:

$$HPC = HPR \times UC \times \left(\frac{1}{4}\right) \qquad (14)$$

Where *HPC* is the total CO_2 emissions rate from the HP (MMSCFD); *UC* is the HP unit utilization capacity (%), and *HPR* is the hydrogen production rate of the unit (MMSCFD). The ratio of CO_2 to hydrogen, obtained from the following equations, is 1:4.

$$C_nH_{2n}+2+nH_2O \rightarrow nCO+(2n+1)\ H_2 \qquad (15)$$

$$CO + H_2O \rightarrow CO_2 + 2H_2 \tag{16}$$

Fluid Catalytic Cracker: in a Fluid Catalytic Cracker (FCC) unit, the low value, high molecular weight compounds are further cracked to produce valuable products (*e.g.* Liquid Petroleum Gas, LPG). Additionally, coke is obtained from a cracking process where it can be used as an energy source in the FCC unit.

The fluid catalytic cracker unit is usually composed of four sections: reaction or conversion, fractionation, gas and LPG recovery, and fuel gas treatment. The main feeds of the FCC unit are heavy gas oil and vacuum gas oils. The former is obtained from catalytic cracking units and the latter from crude units. Also, any heavy petroleum streams can be further treated in the FCC unit.

When this feed enters the FCC unit, its temperature rises to more than 3,169 °C, then interacts with the chemical catalyst (*e.g*. zeolite) before entering the main FCC reactors. After the cracking process, the catalyst is deactivated due to the accumulation of coke on its surface. Steam is usually used to remove coke and keep the catalyst in a fluid state in the reactor.

The FCC unit is responsible for 20-30% of CO_2 emissions from refineries (De Mello, et al., 2009). Carbon dioxide, which results from the burning of coke, is considered as rejected carbon within this unit. This high emissions intensity and center point source make the FCC unit technically suitable for carbon capture techniques.

In Kuwait, there is only one FCC unit, and this is located at MAA, and operates with a capacity of 43 Mbpd.

The total CO_2 emissions from FCC unit at MAA was estimated based on the following the equation:

$$CFP = 0.158OC \times cf \times SG \times UC \tag{17}$$

Where *CFP* is the coke production rate in kg/day; *OC* is the unit operational capacity 43 Mbpd; *cf* is the coke weight fraction in the final FCC product (4.62%); *UC* is the utilization capacity (89.2%); and *SG* is the specific gravity of crude oil at 60°F (900 kg/m^3).

Utility areas (*e.g.* steam, condensate, instrument air, electricity, chemical additives) play an effective role in refineries performance. In a typical complex refinery, heat demand is higher than electrical demand, which explains the numerous numbers of fired heaters and boilers.

A fired heater is responsible for providing heat energy for process fluids (*e.g.* crude oil). The typical fuel composted at fired heaters in refineries is either of low-quality heavy oil or refinery fuel gas (Weydahl, et al., 2013). These waste gases are mainly composed of methane (CH_4), propane (C_3H_8), and hydrogen (H_2).

Utilities are the highest contributor of CO_2 emissions from refineries, followed by FCC units and then hydrogen plants. Almost 65% of CO_2 emissions from refineries come from fired heaters (IEA, 2000).

In Kuwait refineries, fuel gas is the main fuel consumed in the fired heaters, where the number and capacity of these heaters are higher than usual. This is due to the high demand for producing high-quality fuels obtained from heavy crude oil. An emission factor of 73.96 in kg CO_2/MMBTU is used for process heaters.

Acid gas removal unit: natural gas usually contains a high percentage of acid gas, hydrogen sulfide and carbon dioxide, and needs to be treated and made into sweet gas. Several techniques have been developed for this purpose: chemical solvents (amines), physical solvents, adsorption, membranes, and cryogenic fractionation (Althuluth, et al., 2013). Chemical solvent by using amines (*e.g.* Mono-Ethanol-Amine, MEA) is the most mature treatment process and has been used for over 60 years (Herzog, 1999). The treatment unit is composed of two columns: an absorption column and a stripper column.

Before entering the absorber column, sour gas is first sent to the separator to remove any liquids or sand. The solvent is then injected from the top of the absorber column, and the sour gas is introduced from the bottom in a counter-current direction with the solvent. After that, the sweet gas exits from the top of the absorber column, and the solvent with a high concentration of acid gases is sent to the flash drum. Then it enters the stripper column to regenerate again by using steam and start a new cycle. One of the major obstacles of using amines is the high energy needed to create this steam.

An acid gas removal unit currently exists only at MAA, in the gas plant side, and SHU, where Di-Ethanol-Amine (DEA) is used as a solvent in this unit. Di-Ethanol-Amine (DEA) is preferred over MEA for the sweetening process because it can interact directly with acid gases in the same manner as MEA, and it is less degradable and results in less corrosion problems.

An absorber balance equation for CO_2 is usually used to estimate the CO_2 emissions from this process:

$$E(CO_2)=V_{in}[(V_{in}-V_{out})/(1-V_{out})] \quad (18)$$

Where $E(CO_2)$ is the annual volumetric CO_2 emissions from AGR in Standard Cubic Feet per Day (SCFD); V_{in} is the total annual volume of natural gas flow into the AGR in mole fraction, and V_{out} is the total annual volume of natural gas flow out of the AGR in mole fraction.

Electricity imports to the refineries: even though refineries can produce electricity through the steam network, Kuwait refineries are reliant on the Ministry of Electricity and Water (MEW) to meet their electrical demand. Carbon dioxide emissions from this load can be easily estimated by multiplying the default emission factor for electricity generated in Kuwait, which is 870 g CO_2/kWh, with fuel consumption in each refinery.

Al-Salem (2015) identified the main sources of carbon emissions from Kuwait refineries (Table 2-3). This analysis was consistent with Van Straelen, et al. (2010), who reported that fired heaters are the largest contributor to these emissions (62-75%) followed by the Hydrogen Production (HP) unit (12-15%).

Table 2. Carbon dioxide emissions (million metric ton per annum, mtpa) from the three existing refineries in Kuwait

Source	MAA	SHU	MAB
Fluid catalytic cracking (FCC)	0.299	N/A	N/A
Fired heater	3.22[a]	2.22	1.923
Acid gas removal (AGR)[b]	0.027-1.052	0.009	N/A
Flaring	0.063	0.027	0.036
Hydrogen production (HP) units	0.644	0.662	0.653
Electricity load	698.532	343.823	519.817
Total (million tons per year)[c]	3.429	2.921	2.612
% of total in Kuwait (w/o electrical import)	43.544	25.401	21.772

Source: (Al-Salem, 2015)

Notes to readers:

[a] Including gas plant side with refining activities (acid gas sweetening processes and condensate processing).

[b]Total of acid gas removal and condensate sweeting processes combined. A range is calculated based on the type of treated feed. Calculations were based on maximum CO_2 content in acid gas without the electricity load.

[c] Based on maximum CO_2 content in acid gas without the electricity load.

Table 3. Post CFP and NRP CO_2 emissions in Kuwait (mtpa)

Refinery	MAA	MAB	NRP
Total heater emission (post CFP)	2.63	0.907	1.542 x10^3
FCC stack emission	0.299	-	-
Flaring	0.045	0.063	0.081
HP unit	0.898	2.902	2.449
Acid gas removal	1.052	-	-
Total	4.989	3.81	1.54x 10^3

Source: (Al-Salem, 2015)

4.2.3 Petrochemical Based Industry

The petrochemical industry is one of the most significant and leading sectors in the chemical industry, and it accounts for almost 40% of the chemical industry's global market (Ray, et al., 2014). The significant role of this sector results from the strong correlation with other sectors; refinery products and industries dealing with downstream products.

Petrochemical feedstock: feedstock for the upstream petrochemical industry mainly comes from two sources; refinery by-products or natural gas. Selecting a specific feedstock depends on its availability and the demand for the associated end products. The feedstock then takes one of two key pathways: molecular cracking or molecular reforming (Kanchanapiya, 2015).

In molecular cracking, feedstock with large molecules goes through a series of cracking processes to yield smaller molecules. The cracking process can occur either by steam (steam cracker) or catalyst (catalytical cracker). Steam cracking is the heart of any petrochemical facility where the steam requirement varies according to the composition of the feedstock. The products resulting from the cracking process are known as olefins products (*e.g.* ethylene, propylene, mixed C_4, pyrolysis gasoline). In molecular reforming, the target products are yielded by modifying the molecular structure of feedstock through using heat, pressure, catalyst, or a combination of all of them. The products obtained from this process are known as the aromatic group.

The third group is using a synthesis gas to produce ammonia and methanol. These three groups are known as "primary petrochemicals". Polymers are the dominant end products obtained from these groups.

Petrochemical industry in Kuwait: the petrochemical industry in Kuwait began in 1980 and Table 4 illustrates the major petrochemical products produced in Kuwait.

Table 4. Major Petrochemical products in Kuwait (Mt)

Product		2010
Fertilizers	Urea	1.05
	Ammonia	0.66
Olefins	Ethylene	1.65
	Polyethylene	0.9
	Ethylene glycol	1
	Polypropylene	0.15
Aromatics	Paraxylene	0.83
	Benzene	0.4
	Styrene monomer	0.45
Total		7.1

Source: (CBS, 2015)

Carbon dioxide emitted from the petrochemical industry: to assess the CO_2 emissions of the petrochemical industry, three main sources of energy consumption were identified; fuel consumption with the largest share (60%), steam energy consumption (35%) and electrical consumption (5%) (Benchaita, 2013). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are emitted from fuel consumption when conventional fuels are used: naphtha, ethane, and LPG.

- Ethylene is one of the main secondary products obtained from the steam cracker, where it is utilized in the production of various petrochemical derivatives. The ethylene production process is an intensive energy process, and its global production rate has an annual increase of 4-5% (Kolmetz, 2013).
- Steam cracker components in an ethylene plant will be considered further to identify CO_2 emission sources.

Steam Cracker Furnace: feedstocks introduced to a steam cracker furnace are exposed to high pressure, and the temperature from the pyrolysis furnaces reaches 1,100 °C. As a result, hydrocarbon breaks down into smaller molecules.

The following reactions are the predominant reactions that usually occur:

$$\text{Ethane } (C_2H_6) \rightarrow \text{Ethylene}(C_2H_4) + H_2 \quad (19)$$

$$\text{Propane } (C_3H_8) \rightarrow \text{Ethylene}(C_2H_4) + CH_4 \quad (20)$$

$$\text{Propane } (C_3H_8) \rightarrow \text{Propylene}(C_3H_6) + H_2 \quad (21)$$

Quench Tower: steam generated from the previous process and pyrolysis gasoline components condense in a quench tower, which is used as a partial condenser for fractionators. Heat absorbs at various levels in the quench tower through the heat transfer section. Significant amounts of heat obtained from this process are utilized in another unit.

The rest of petrochemical processes mainly focuses on further cracking of the feedstock:

Gas Compression: this stage considers the primary stage of separation, where some of the products are obtained after compression. The main function of the compression stage is preparing the feedstock for the final fractionation.

The pressure of gas fraction increases to about 3,500 kilopascals (kPa) by using a centrifugal compressor. The compression unit is usually divided into five stages where liquefied components are separated after each stage.

Cracked gas contains both water and other impurities that need to be removed. These impurities are mainly composed of CO_2, hydrogen sulfide (H_2S), and acetylene. Carbon dioxide and H_2S were removed in the caustic tower. Water was removed by the dehydration process, and the condensate steam obtained from this process is reused again. The Cracked Gas Compressor (CGC) is the major consumer of energy in the entire ethylene plant.

Chilling Train: the chilling train is composed of a series of heat exchangers with refrigeration. Most of the heavier hydrocarbons are condensates in this unit, producing a stream of hydrogen:

$$C_2H_6(g) \rightarrow C_2H_4(g) + H_2(g) \tag{22}$$

Fractionation and Separation: typical fractionation and separation units are mainly composed of three sub-units: distillation, refrigeration, and extraction. Three towers are usually found in the distillation unit: de-methanizer, de-ethylenizer, de-ethanizer.

As previously mentioned, there is a direct relationship between the energy intensity of the steam cracker and CO_2 emissions. These emissions will vary according to certain variables: types of feedstocks, design of cracker components, and operational conditions.

The European Chemical Industry Council, representing European steam crackers, supports the linear relationship between ethylene production and CO_2 emissions (Benchaita, 2013). By applying the above correlation to the Kuwait petrochemicals sector, the total expected CO_2

emissions, from producing 1.65 Mt of ethylene, was determined to be 2.642 MtCO_2/y for the year 2016.

4.3 The Cement Industry

Limestone (calcium carbonate, $CaCO_3$), sand, and clay are the main raw materials used for cement production. Within a ball mill, specific quantities of these raw materials are ground to yield a powder. This powder takes either one of two pathways: wet process or dry process. In the wet process, the grinding process occurs in the presence of water. The slurry obtained from this process goes through further mixing before being transferred into the kiln. The wet process is favored when the raw material is humid, as is the case in most countries.

In the dry process, to obtain a homogenous mixture of a ground powder suitable for the grinding stage, the powder first goes through a blending silo. After that, the mixture enters the preheater/calciner before transferring to rotary kilns. In the preheater/calciner process, hot gases are used to raise the temperature of the mixture that leads to calcination of limestone where calcium carbonate breaks down to calcium oxide and CO_2 is emitted from the reaction. Clinker is formed in rotary kilns by pyrprocessing, and cement minerals are formed through the evaporation of the existing water. After washing, the clinker is moved to a clinker storage silo and sent to a finish mill. Next, comes the cooling process which is used to eliminate the formation of the glass phase and to obtain the maximum percent of alite (tricalcium silicate). Finally, the clinker is ground, along with 3-5% gypsum, to form cement.

The cement industry is the main producer of global CO_2 emissions from non-energy sources (IPCC, 1997), and it is responsible for 7% of global CO_2 emissions (Malhotra,1999). Direct carbon emitted from cement production is derived from two main sources, the calcination process and the combustion of fossil fuel. The indirect emissions are derived from electricity consumed in the cement plant.

In this analysis, the *Tier 2* method of IPCC (IPCC, 2006) was applied. The EF value suggested by the IPCC is 0.459 metric tons (t) CO_2 per t clinker produced. IPCC added 2% of the CO_2 calculated because of the loss of some clinker raw materials as calcinated Cement Kiln Dust (CKD). The final equation to estimate CO_2 from calcination processes was therefore applied:

$$H = 1.02EF \times C \tag{23}$$

where H is the process related emissions Mt CO_2/y; EF is the emission factor of 0.459 in t

CO_2/ t Clinker produced, and *C* is the clinker production in metric ton/ year (t/y).

By applying Equation 23 in the Kuwait cement industry, where the annual clinker production is 1,800,000 t (Mineral yearbook, 2013), the process-related CO_2 is estimated to be 0.165 Mt CO_2/y. The intensity of CO_2 emissions will vary according to the type of fuel used, and manufacturing operations within the cement industry. Due to a shortage of data regarding fuel consumption in Kuwait's cement factories, the estimated value previously suggested by (Mineral yearbook, 2013) equals 0.306 Mt CO_2/y during 2011 and was used in the analysis. From the above values, the total CO_2 load from the cement industry of Kuwait from both processing and fossil fuel combustion is 0.322 Mt CO_2/y.

4.4 Aluminum Manufacturing Industry

Aluminum is obtained from two pathways, either from natural resources (*e.g.* bauxite) or recycling of scrap metal. Alumina is the main component of bauxite. If alumina is used to produce aluminum, this process is known as primary production and the resulting aluminum is called primary aluminum. If recycled scrap metal is used, the process is known as a secondary process and aluminum is called secondary aluminum. The demand for aluminum alloy does not differentiate either; it comes from primary or secondary production.

Aluminum production process

Mining of bauxite ore is the first stage of primary aluminum production. Bauxite consists of impurities, such as aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), and silica (SiO_2). The refining of bauxite to alumina is known as the Bayer process.

During this process, preheated sodium hydroxide (NaOH) is added to bauxite ore after the bauxite has been dried and grounded in ball mills. Sodium hydroxide (NaOH) is used to dissolve the aluminum-bearing minerals which exist in bauxite. The slurry obtained from this process is dispatched to a pressurized digester that operates at 105 to 290 °C. After spending almost five hours in the pressurized digester, the slurry is cooled to 100 °C. This slurry is primarily composed of sodium aluminate ($NaAl_2OH$) solution and insoluble red mud. The solution containing the alumina, which overflows from setting tank, is further purified by filtration and then cooled. Alumina precipitates out from the cooled solution as alumina tri-hydrate. Crystalline form of alumina is obtained from calcining of the alumina tri-hydrate after being washed and filtered. Crystalline alumina dissolved in electrolyte bath consists of molten cryolite (sodium aluminum fluoride), this process known as “Hall-Heroult smelting”. Due to electricity movement, aluminum metal accumulates at the cathode while the anode will contain oxygen gas. The cathode in the smelting cell is a carbon-lined steel box and a row of graphite and petroleum coke while pitch forms at the carbon anode.

To assess the CO_2 emissions from the aluminum (Al) manufacturing processes, three main sources of emissions are identified:

- Combustion of fossil fuel (direct-energy related emissions).
- Electricity used in the smelting process (indirect-energy related emissions), which are responsible for the biggest proportion of the emissions.
- Emissions during the electrolysis process (process emissions) where both CO_2 and Per-Fluoro-Carbon gases (PFCs) are emitted (Colombia Climate Center, 2016).

The anticipated CO_2 emissions can be estimated from the following equation (EPA, 2002):

$$Y = EF \times C \tag{24}$$

where Y is the total CO_2 emissions from Al production in t/y; EF is the emission factor, which is 1.4 t CO_2/ t Al and C is the Al production in t/y. According to the GCC Industry Report (Gulf Capital Group Limited, 2008), the total aluminum produced in Kuwait is 0.108 Mt/y. Therefore, by applying Equation 24, the carbon footprint of the aluminum sector in the state is 0.167 Mt CO_2/y showing a considerable variation which can be attributed to changes in Al production and market over the past decade.

4.5 Iron and Steel Industry

Three known pathways are used to produce iron by chemically reducing iron ore: Blast Furnace (BF)/Basic Oxygen Furnace (BOF), smelting reduction, and direct reduction. Additionally, Electric Arc Furnace (EAF) is used to produce steel by the melting of scrap. Almost 65% of steel manufactured is obtained from BF/BOF while the remaining 30% yields from EAF (World Steel Association, 2011). Raw materials used for iron and steel production can be prepared by one of the following processes:

- Sintering production.
- Pelletizing.

- Coke Making.

Iron making

Blast Furnace: in a blast furnace, iron ore, coke, and limestone are introduced from the top of the furnace and hot air is blown in from the bottom. Coke burns in hot air, forming carbon monoxide (CO); this CO works as a reducing agent of iron oxide to release iron. Coke can also be used as fuel in this furnace.

Due to the high temperature, the material is converted into liquid slag and liquid iron, and they are removed from the furnace at regular intervals. The main function of this furnace is to produce hot metal from reducing iron oxide.

Direct Reduction: a reducing gas, composed mostly of hydrogen (H_2) and CO, is used for the direct reduction of iron ore in its solid-state to yield Direct–Reduce Iron (DRI). This route is competitive in the GCC region due to the abundant availability of natural gas.

Smelting Reduction: this method combines iron ore reduction with smelting in a reactor; the method was developed to replace a blast furnace process and reduce the substantial levels of energy used in the furnace. This pathway can also obtain molten, slag-free iron. Although BF will not be quickly replaced by smelting reduction, however, due to its high thermal and chemical efficiency, many smelting reductions processes have now achieved commercial stage level.

Steel

Basic Oxygen Furnace (BOF) is the dominant steelmaking technology used globally. It transforms molten pig iron and steel scrap into steel; this occurs by the introduction of oxygen to the hot metal.

Electric Arc Furnace (EAF) was developed to replace BF/BOF route. In this furnace, ferrous scrap is recycled to yield carbon steel and alloy steel. When ferrous scrap is not available, DRI and pig iron can substitute it. In EAF, liquid steel obtained from the furnace is transmitted to a Ladle Metallurgy Station (LMS) to improve the quality of the yielding steel.

Casting, Rolling, and Finishing: molten steel is yielded from the LMS process to a continuous caster and this gives the steel its semi-finished shape. To get the final shape of the steel, steel from the continuous caster is handled in rolling mills. This process is the main source of indirect CO_2 emissions due to its high electricity consumption. The final stage is a finishing process that involves acid pickling, painting, galvanizing, tinning, and plastic coating to meet the market's demands.

Iron and steel are the largest contributors of CO_2 emissions among all industrial processes. This is mainly due to the high demand for steel in certain sectors (*e.g.* construction, transport, energy, packaging, appliances, and industry), type of fuel used, and the high-energy intensity of steel production (IEA, 2012a). Carbon dioxide emissions from iron and steel production are obtained from three main sources:

- Process emissions from sinter plant, non-recovery coke oven battery combustion stack, coke pushing, BF exhaust, BOF exhaust, and EAF exhaust (EPA, 2012).
- Combustion of fossil fuel in furnaces and utilities including byproduct recovery coke oven, battery combustion stack, BF stove, boiler, process heater, reheat furnace, flame-suppression system, annealing furnace, flare, ladle re-heater, and other miscellaneous processes (IEA, 2013a).
- Emissions from electricity consumption, mostly from EAFs and finishing operations.

International Energy Agency (IEA) methods are used in this analysis rather than Intergovernmental Panel on Climate Change (IPCC) guidelines due to the limited availability of data of electricity and fuel consumption in the iron and steel manufacturing processes of Kuwait. The value of the CO_2 emission factor will vary according to the selected pathway used to produce the steel**.** The emission factor is estimated to be 2.267 t CO_2/ t crude steel for coal-based Direct Reduced Iron (DRI) process, 1.632 t CO_2/ t for integrated Blast Furnace (BF) and Basic Oxygen Furnace (BOF). For scrap /Electric Arc Furnace (EAF), it decreased to 0.362 t CO_2/ t crude steel (EAF) (IEA, 2013a).

By applying the above-mentioned emission factors to the United Steel Company and Kuwait Reinforced Steel Manufacturing Co., CO_2 associated with the production of 544,311 t of steel using EAFs (Kuwait Steel, 2016) is 0.197 Mt CO_2/y. In Kuwait, the emissions associated with the production of 0.317 Mt (namely from the reinforced steel company) per year are equal to 0.114 Mt CO_2/y.

Table 5 details the CO_2 associated with the production of 1 kilometer of steel pipe. The volume of the pipes produced ranged from 129.7 to 1167.4 m^3. A comparison will take place between the dimensions of Table 5 with the dimensions of steel pipe produced by Kuwait Pipe Industries. The thickness of these pipes ranges from 4.8 to 25.4 mm and 0.168 to 2.032 m in diameter, and the length is between 6 to 16 m. As a result, the volumes of these pipes are between 0.133 to 52 m^3, and the associated CO_2 emissions are from 121.3 to 883.32 t / km pipe. Based on the above results, the total anticipated CO_2 emissions from iron and steel industry in Kuwait is 0.32 Mt CO_2/y.

Table 5. Carbon dioxide emissions for steel pipe production

Diameter (inch)	Thickness (mm)	Weight (ton/km pipe)	Carbon dioxide emissions (metric tons/km pipe)			
			Blast furnace	Continuous casting	Rolling and pipe production	Total
16	7.95	70.669	109.497	0.997	10.795	121.29
20	9.82	109.134	169.099	1.542	16.692	187.242
24	10.25	136.622	211.827	1.905	20.865	234.597
36	14.35	286.942	444.792	3.991	43.817	492.601
48	19.30	514.555	797.596	7.166	78.652	883.325

Source: (NACAP, 2010)

4.6 Chemical Industry

The chemical industry is one of the highest-energy intensive sectors and is responsible for 10% of global energy consumption and 7% of global GHGs emissions (ICCA, 2013). The products yielded from this industry can be generally classified into basic chemicals (*e.g.* polymers), specialty chemicals (*e.g.* adhesives), and consumer chemicals (*e.g.* soaps). These products have a significant role in meeting basic needs and improving the quality of life. Table 6 describes some examples of the chemicals industries operating in Kuwait and their geographical location.

Table 6. Examples of some chemicals industries operating in Kuwait and their geographical location

	Description	Location
Asphalt production	Bitumen is a thick mixture of hydrocarbons obtains from the oil distillation process during the refining of crude oil. Asphalt is one compound of this mixture that has both binding and chemical isolation properties. Asphalt is mainly used in road surfacing, roofing, coating, and floor tiling.	Twenty companies clustered in two industrial areas: Amghara and Sulaibiya
Lubricating oils and greases	Lube oil is another crude oil derivative, extracted from the fractionating tower. The oil then undergoes a further purification process to remove contaminates and aromatic compounds. Additives are added to lube oil and grease to give them the required physical properties.	Three companies in Shuaiba industry area
Industrial Gases	The most common gases produce for industrial purposes are acetylene (C_2H_2), hydrogen (H_2), carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), and argon (Ar). Some of these gases are by-product of other industries (*e.g.,* CO_2 obtained from the natural gas plant) while others can be manufactured (*e.g.,* C_2H_2 is producing from the reaction of H_2O with CaC_2).	Six companies, five of them are in Shuaiba and one in Shwaikh industrial area
Glue	Glue is a liquid adhesive obtained from organic compounds. Animal remains from tanneries, slaughterhouses, and meat packing companies are the main suppliers of the raw materials used to produce glue.	Three glue manufacture companies. One is in Amghara industrial area and the other two are the Sabhan industrial area
Pesticides	Pesticides are a group of chemicals used to limit a wide range of plant problems. According to their target pests, they classified into fungicides, herbicides, and rodenticides.	One factory in Shuabia and another in Amghra industrial area

Table 6. Examples of some chemicals industries operating in Kuwait and their geographical location, continued

	Description	Location
Perfume	Several raw materials are used to manufacture perfume, some of them comes from natural sources (*e.g.,* fruit) while others from synthetic chemicals.	Five perfume factories, three of them situated in Sabhan while the remaining two in Shuaiba and Amghara industrial areas
Detergents	Are mainly composed of two portions, oil or fat, and alkali. The prevailing alkali uses are sodium hydroxide and potassium hydroxide.	Kuwait has eight detergent manufacture factories, five of them in Sabhan, two in Amghra and one in Shuaiba industrial area
Plastic products	Plastic products were invented to reduce the pressure on depleted natural resources (*e.g.* wood, horn, and rosin) where they mimic the properties of these resources. In general, plastic can be classified into two main classes, thermoplastic and thermosetting plastics. The fundamental difference between these two classes is in bond connecting the molecules in the long-chain structure.	Kuwait plastic factories are widespread among all industrial areas
Other chemical elements	This family of chemical additives and agents includes catalysts, corrosion inhibitor, scale inhibitor, anti-bacteria, and emulsion breaker.	Three Kuwaiti companies located in Shuaiba industrial area.

Carbon dioxide emissions are generated throughout the entire life cycle of a chemical product starting from the extraction of raw materials to the recycling process. The Public Authority of Industry in Kuwait categorized the chemical factories in the state according to their end products. Table 7 indicates the quantities of each synthetic product produced during 2010 and the anticipated CO_2 emissions from the production processes (Appendix K).

Based on this result, the total CO_2 emitted from the chemical industry is 31.9 Mt/y. This estimate was decreased by 20% to avoid double counting with electricity consumed in this sector. This percentage was obtained from personal communications with personnel in both the Public Authority of Industry and the chemical factories, as electrical input to the chemical industry in Kuwait is taken as part of the power sector assessment. This makes the final carbon footprint of the chemical sector in Kuwait to be 25.45 Mt/y.

Table 7. The anticipated CO_2 emissions from Kuwait chemical industry. Adapted from Public Authority for Industry data.

Product	Production (million Kg) in the year 2010	Emission factor (t CO_2/Kg)	Carbon dioxide emission ($MtCO_2$/y)
Asphalt	5,654	0.00186	10.517
Detergents	292	0.00175	0.511
Plastic products			
Plastic in primer form	2.747	0.0027	0.00741
GRP pipes	13	0.0081	0.107
Plastic produced for building boats	0.19	0.0027	0.000514
Total plastic produced for floor, ceiling, walls, coverings in the form of tiles or rolls	9.802	0.0027	0.0264
Total plastic produced for shoes and sandals	2.041164	0.0027	0.00551
Total plastic produced in curtly	36.66	0.0027	0.0989
Fertilizers	1502.908	0.00462	6.943
Paints	32.591	0.0054	0.175
Lubricating oil and greases	62.63	0.00107	0.067
Industrial gases			
Oxygen	1,463.43	0.00041	0.6000081
Nitrogen	4729.954	0.00043	2.033
Hydrogen	4525.222	0.00163	7.376
Carbon dioxide	0.8001	0.00082	0.000656
Sulfuric acid	44.515	0.00014	0.00623

Table 7. The anticipated CO_2 emissions from Kuwait chemical industry, adapted from Public Authority for Industry data, continued

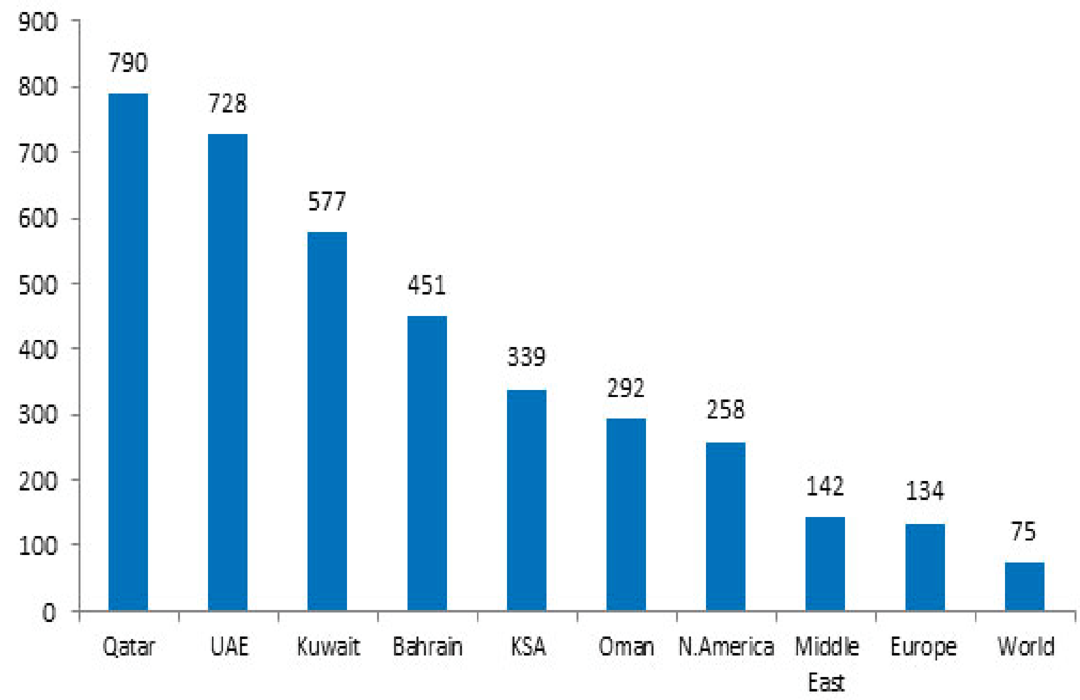
Product	Production (million Kg) in the year 2010	Emission factor (t CO_2/Kg)	Carbon dioxide emission ($MtCO_2$/y)
Other chemicals	1131.752	0.003	3.395
Total	19,505.11		31.873
Total (-20%)			25.45

4.7 Paper

Globally, pulp and paper production are responsible for 3% of direct CO_2 emissions from industry (Carbon Trust, 2011). The CO_2 emissions from paper production have been investigated by various authors (Leon, et al., 2015; NCASI, 2005; Shabbir and Mirzaeian, 2017), where steam production and electricity consumption are the main causes of these emissions. Kuwait has more than seventy companies specializing in paper production; most of them located in the Sabhan and the Shuaiba industrial areas. From the data available from the Food and Agriculture Organization (FAO, 2014), the total paper produced in Kuwait during 2013 was 432 million kg. The corresponding emission factor of paper production is 0.00242 t /kg. In conclusion, the associated CO_2 emissions from paper manufacturing processes are estimated to be 1.045 Mt CO_2/y.

4.8 Power Stations & Water Desalination Plants

Kuwait is one of the world's smallest countries; however, it ranked as one of the highest per captia in energy consumption (Figure 28) (IEA, 2012a). The MEW owns and operates all power stations in Kuwait and their associated facilities. The MEW sells subsidized electricity and water for both commercial and domestic consumers. There are two main reasons behind the high consumption levels in Kuwait. First, the ultra-low cost of electricity in the country where the government takes responsibility for 95% of electricity costs and citizens and factories pay only 5% of the cost (CBS, 2015).



Source: (MARKAZ, 2015)

Figure 28. Primary energy consumption per capita (million Btu Person)

Second, the summer in Kuwait is one of the longest and hottest seasons in any country of the world starting from April until mid-November with an outdoor temperature often exceeding 50 ºC. Additionally, rapid growth in population (an average growth rate of 3.3%) has also contributed to increased electricity consumption (Alotaibi, 2011).

To overcome the peak demand during summer, Kuwait, in conjunction with all other GCC countries, constructed a huge, interconnected grid project that allowed all GCC members to share electricity during the peak season. In length, this grid is 900 km, starting from Kuwait and ending in Oman (Figure 29). It consists of seven 400 kilo-Volts (kV) sub-stations along the 900 km of overhead lines, in addition to an 1800 Megawatt (MW) three-pole back-to-back High Voltage Direct Current (HVDC) converter station and a submarine cable to Bahrain.

Source: (Aljohani and Alzahrani, 2014)

Figure 29. The geographical routes and layouts of the GCC interconnection

Kuwait has seven power stations, namely Shuwaikh (252 MW), Shuaiba North (876 MW), Shuaiba South (720 MW), Doha East (1158 MW), Doha West (2360 MW), Al-Zour (5306 MW) and Sabiya (4867 MW). The unique feature of these power stations is their ability to produce both Electrical Power (EP) and Desalinated Water (DW) simultaneously. Several forms of fossil fuels exist in Kuwait and can be used in these power stations including natural gas, crude oil, heavy fuel oil, and gas oil. The source of power generation in these stations is divided between thermal steam turbines (85%) and gas turbines (15%) (Figure 30) (Savsar, et al., 2012).

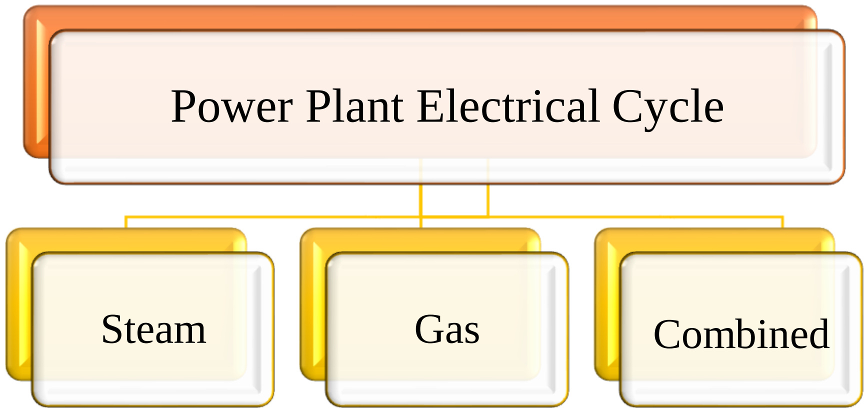


Figure 30. Power plant electrical cycle

Steam cycle power station is the ideal prime mover to convert thermal energy in pressurized steam into kinetic energy and then into useful mechanical work. Certain parameters must be considered when designing a steam turbine including 1) electricity demand 2) steam conditions 3) ambient temperature 4) power plant configuration. The efficiency of the steam turbine power plant ranges from 35 to 45% depending on the temperature of the created steam (Hussan, et al., 2014). Sabiah power station is the only steam station operating in Kuwait, where fossil fuel is burned in the boiler to generate the required steam with high pressure and temperature. Then the generator uses this steam via a turbine to produce the electricity needed. After electricity is produced, the steam is condensed so that it can be reused again in the cycle after treating it chemically to avoid corrosion issues.

Gas cycle power station: this type of power station is usually used as a complementary station during the peak load due to their low capacity for electricity production. This peak load occurs in Kuwait during the summer season, especially in July and August. In these stations, the production of electricity starts with compression of ambient air, which is mixed with fuel and burnt in the combustor. Then, the turbine receives this air-fuel mixture and produces electricity (Figure 31). The only gas turbine station present in Kuwait is the Al-Zour gas power production station.

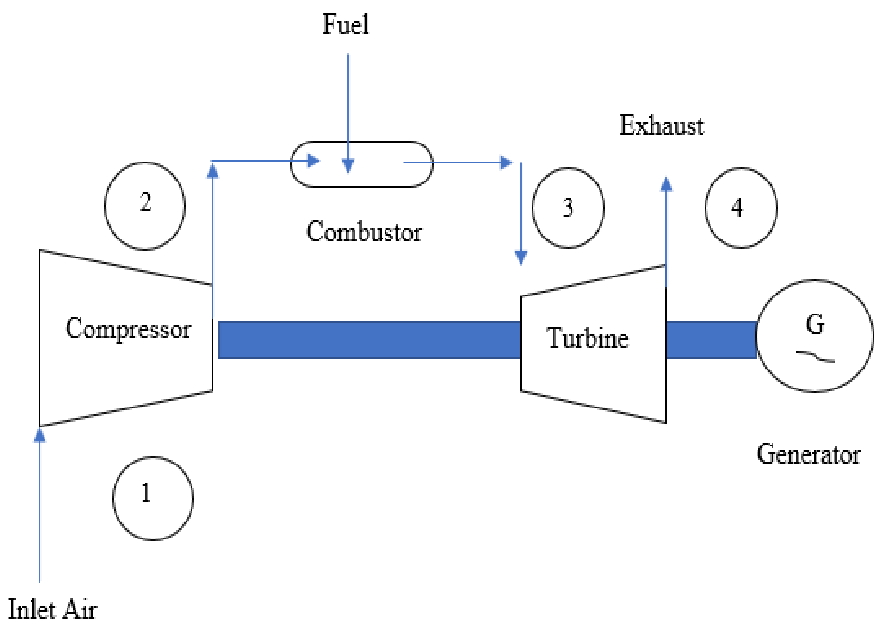


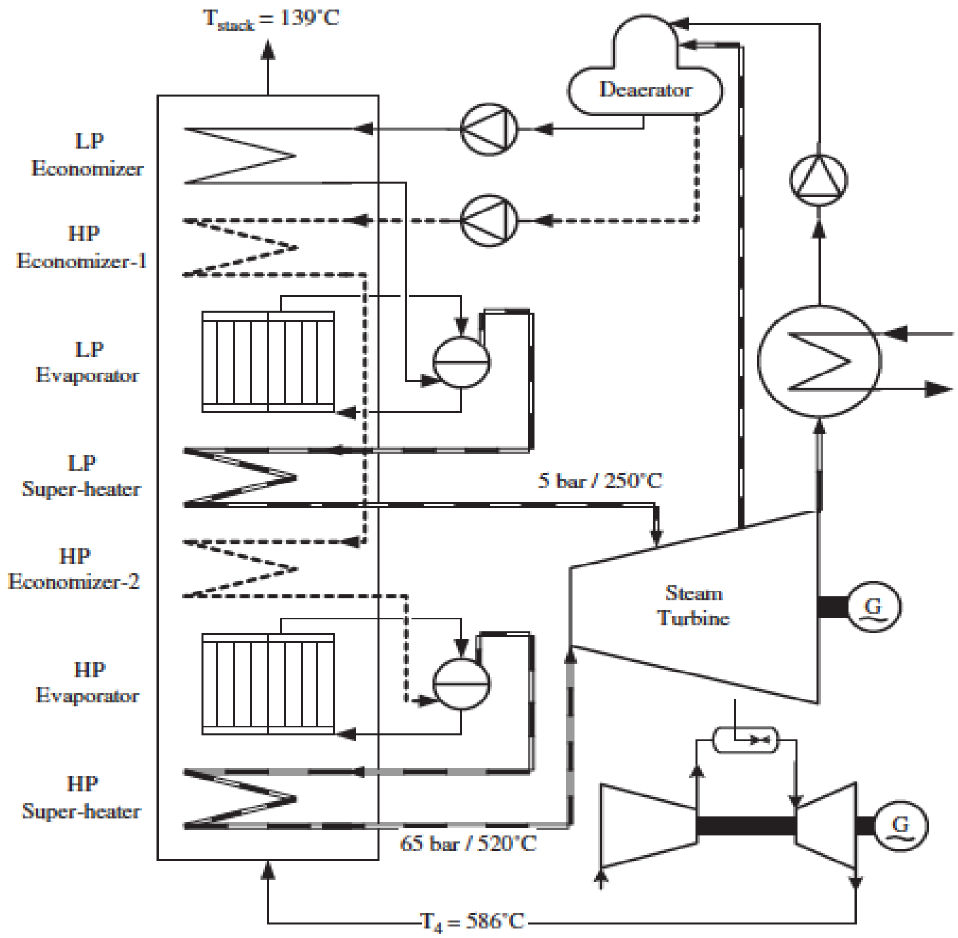
Figure 31. Simple-cycle single-shaft gas turbine adapted from (Darwish, et al., 2008)

Combined cycle power station: as the name implies, the combined cycle station contains both steam and gas turbines to obtain the required electricity. By using combined cycle technology, the overall efficiency of power plants is improved in addition to consuming a smaller amount of fuel (Hussan, et al., 2014). In this cycle, the steam turbine uses the exhaust gas obtained from the gas turbine to produce additional electricity (Figure 32). This process occurs through the Heat Recovery Steam Generator (HRSG). Table 8 represents the total capacity of both steam and gas turbines in the current power stations located in Kuwait.

Table 8. Power Stations available capacity (M.W) in 2013

Stations	Current available capacity				Total availability capacity
	Gas turbine		Steam turbine		
	Capacity of each unit	Total	Capacity of each unit	Total	
Shuwaikh station	6 x 42	252	-	-	252
Shuaiba South station	-	-	6 x 120	720	720
Shuaiba North station	3 x 2 20	660	1 x 215.5	215.5	875.5
Doha East station	6 x 18	108	7 x 150	1050	1158
Doha West station	5 x 28.2	141	8 x 300	2400	2541
Al-Zour South station	8 x 130 4 x 27.7 5 x 165	1040 110.8 825	8 x 300 2 x 280 2 x 185	2400 560 370	5305.8
Sabiya station	6 x 41.7 4 x 62.5 6 x 220	250.2 250 1320	8 x 300 3 x 215.5	2400 646.5	4866.7
Total		4957		10762	15719

Source:(CBS, 2015)

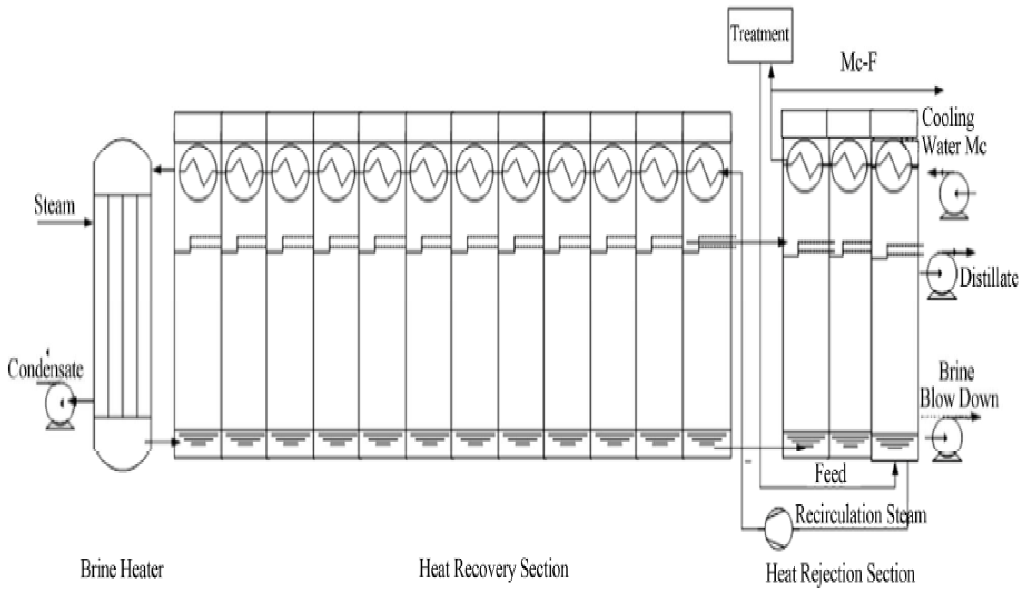


Source: (Darwish, et al., 2008)

Figure 32. Combined gas turbine and steam turbine cycle with two-pressure stage HRSG

Desalinated unit: Kuwait is an extremely water-stressed country and is heavily dependent on the desalination of seawater to satisfy its growing freshwater demand. Groundwater is the sole source of renewable freshwater, and it represents only 7% of the freshwater sources while the desalination process provides the remaining 93% (Darwish, et al., 2009).

The per capita consumption of water in Kuwait is one of the highest in the world, at 500 (liter per day) (Luomi, 2014). The Multi-Stage Flash (MSF) process is the only process used in CPDP power stations to produce desalinated water, and it is one of the most energy intensive consumption processes (Figure 33). The Multi-Stage Flash (MSF) is connected to the steam turbine to use the steam efficiently.



Source: (Darwish, 2013)

Figure 33. The multistage flash desalination flowsheet

Table 9 indicates the fuel consumed in all Kuwait power stations during the period 2005 to 2013 and the associated CO_2 emissions from this period. Based on Table 10 the estimated CO_2 emitted from power stations is 41.6 Mt/y from 2009 to 2016 (Est.) (Appendix L).

Table 9. Fuel consumed in Kuwait power stations during the period 2005-2013 according to (CBS, 2015)

Fuel (million ton)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	0.088	0.488	0.444	0.784	1.221	1.0241	1.154	1.342	1.0410
Heavy fuel oil	5.223	5.972	5.461	6.283	4.992	4.947	4.387	4.345	5.293
Natural gas	2.284	3.112	3.237	3.631	3.783	5.285	6.080	6.654	6.387
Crude oil	2.177	1.169	1.867	1.0666	2.264	2.0244	2.191	1.867	1.276

Table 10. Carbon dioxide emitted from fuel consumed in Kuwait power stations during the period 2009-2016. Estimates were taken from (KNPC, 2016)

Anticipated carbon dioxide emission ($MtCO_2$/y) from	2009	2010	2011	2012	2013	2014 (Est.)	2015 (Est.)	2016 (Est.)
Gas oil	3.555	2.9809	3.361	3.907	3.03	2.88	2.738	2.6
Heavy fuel oil	14.115	13.989	12.406	12.286	14.965	16.508	18.211	20.08
Natural gas	9.437	13.186	15.169	16.601	15.934	16.335	16.747	17.17
Crude oil	6.401	5.723	6.196	5.278	3.608	2.854	2.258	1.786
Total	33.511	35.881	37.133	38.075	37.538	38.577	39.954	41.636

Future of energy in Kuwait

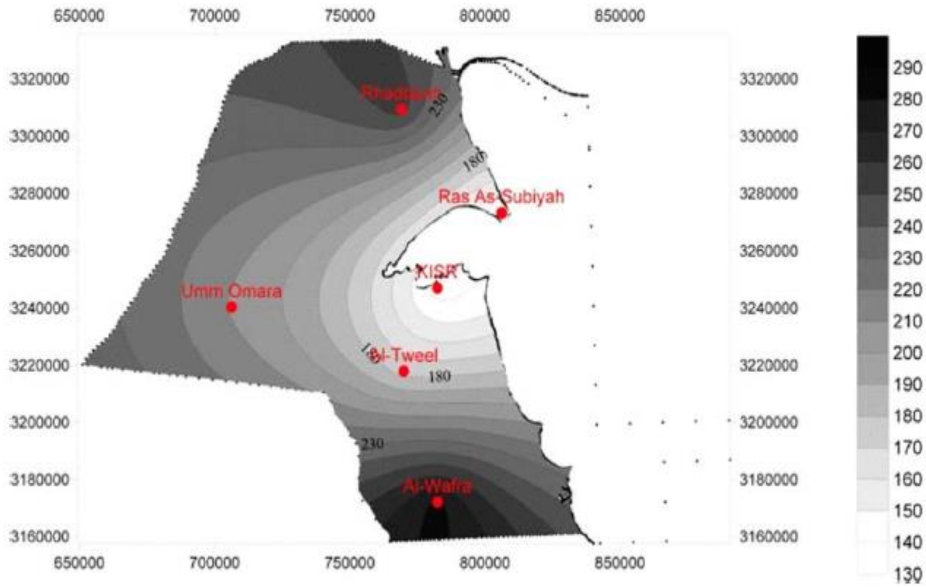
New power stations: the national government of Kuwait has plans to establish several power stations to meet the high future demand for electricity. Khairan Power Plant is a governmental project that had been completed in 2018, while Al-Zour North represents the main Public-Private Partnership (PPP) project.

Under the government's vision of decreasing the consumption of crude oil in the energy sector and releasing it to export, the new plants are designed to consume natural gas as the main fuel. Using natural gas will reduce the CO_2 emitted from power stations due to its lower carbon content. These new power stations will raise the total electrical capacity of Kuwait by 140% during the period 2014 to 2019 (CBS, 2015).

Nuclear energy: Kuwait has previously shown a clear intention to construct nuclear energy plants in the next 20 years. The process began when the government of Kuwait signed a cooperative deal with the French Atomic Energy Commission to establish the first nuclear energy plant with work due to begin in 2022 on four nuclear reactors. However, in 2011, Kuwait suspended this plan due to the huge disaster that occurred in Japan from radiation leakage at the Fukushima nuclear plant.

Solar energy: the peak demand for electricity in Kuwait is in the afternoon period during summer (12:00-14:00) due to the maximum solar radiation at this time. This offers an excellent opportunity to use this tremendous amount of radiation as a renewable source of energy. Both Photo-Voltaic (PV) and Concentrated Solar Power (CSP) have enormous potential to be used in Kuwait (Ramadhan and Naseeb, 2011). Al-Hasan, et al. (2004) illustrated that the peak demand could be reduced by 20% by using a 1000 (MW) fixed (PV) system. The first solar plant to be constructed in Kuwait is the Al-Abdaliya project. This project will use both solar and combined cycle units where solar cells are planned to produce 60 MW out of 280 MW. The main feature of the combined plant is having less CO_2 emitted to the atmosphere by almost 44,000 t, compared to a conventional plant with the same capacity (Kuwait Authority for Partnership Projects, 2018). Construction of this plant is under Kuwait's plan for increasing the participation of renewable energy to 15% by 2030.

Wind energy: the second renewable source of energy that has an enormous potential to be utilized in Kuwait, is wind energy. It is due to the desert feature of the state where high wind speeds are experienced in specific locations. Figure 34 indicates that the wind speed in six locations in Kuwait, at a height of 10 m, ranged between 3.7 to 5.5 meters per second (m/s), and it was mainly concentrated in the northwest of the country. This wind has an acceptable density from 80 to 167 (W/m^2) to construct a wind farm in the Kuwaiti desert (Table 11).



Source: (Al-Nassar, et al., 2005)

Figure 34. Distribution of wind power density over Kuwait at 30 m height

Table 11. Wind characteristics in six locations in Kuwait at 10 m height

Station	*V (m/s)*	*K*	*C (m/s)*	Mean WPD (W/m^2)	Predicted WPD (W/m^2) KISR 4.07
Kuwait Institute for Scientific Research (KISR)	4.07	2.25	5.22	84.03	80.06
Al-Taweel	5.33	2.64	6.79	105.99	150.50
Rawdatain	3.87	2.21	5.26	45.02	80.93
Ras As-Subiyah	4.76	2.08	5.36	98.90	103.94
Umm Omara	4.88	2.19	5.83	97.94	123.42
Al-Wafra	5.52	2.70	7.18	122.71	166.68

Source: (Al-Nassar, et al., 2005)

4.9 Building and Construction

As a result of oil discovery in Kuwait, major economic growth resulted in the expansion of the urban sector of the state. Buildings are responsible for 30% GHGs emissions in both developed and developing countries (UNEP, 2015). Operational energy is the main source of CO_2

emitted from buildings; it includes heating, cooling, and lighting systems, in addition to all machines used in kitchens, offices, etc. In Kuwait, this energy translated into electrical energy obtained from MEW and energy from LPG and kerosene used for the household sector.

Table 12 illustrates the average electricity consumed by apartments and villas in Kuwait during 2009. To avoid double counting between CO_2 emitted from the power plants and electricity consumption in buildings, this sector will cover only the carbon emitted from household consumption of LPG and kerosene.

According to the Ministry of Oil database (MO, 2016), the household consumption of LPG during 2009 was 1.508 million barrels. The LPG per capita consumption is estimated to be 16.492 gallons.

$$W = D \times EF \tag{25}$$

Where W is the total CO_2 emitted from LPG consumption during 2013 Mt CO_2/y; D is the household consumption of LPG, and EF is the emission factor of 0.0058 t /gallon. It makes the total anticipated CO_2 emissions from LPG consumption 0.405 Mt/y, and similarly, kerosene is responsible for 0.14 Mt CO_2/y with an emission factor of 0.00976 t /gallon kerosene. Based on the above results, the total CO_2 emitted from Kuwait's buildings during 2016 is 0.54 Mt CO_2/y.

Table 12. Average electricity consumption by apartments and villas in Kuwait, 2009

Kuwait					UK (2013)	
Dwelling Type	Number of dwellings	Electricity consumed			Average kWh/ dwelling/ annum	Average kWh/m²/ dwelling/ annum
		Share	Average kWh/ dwelling/ annum	Average kWh/m²/ dwelling/ annum	4,170(electricity) 14,829 (gas) Total – 18,999	209
Villas	105,764	88%	145,444	264		
Apartments	170,815	12%	20,278	127		

Source: (Jaffar, et al., 2014)

4.10 Transportation Sector

The transportation sector is responsible for 20% of global CO_2 emissions (Herzong, et al., 2005). In Kuwait, two transportation modes are available to the public: road and air transport. Shipping is only used for commercial purposes.

Road transportation

Vehicles on Kuwaiti roads can generally be categorized as private or commercial. The Ministry of Interior (MOI) stated that the total number of vehicles on Kuwaiti roads increased by 162% during the period 2005 to 2014 with a 61% increase in the number of private cars (average of one car for every two residents of the state) (Figure 35).

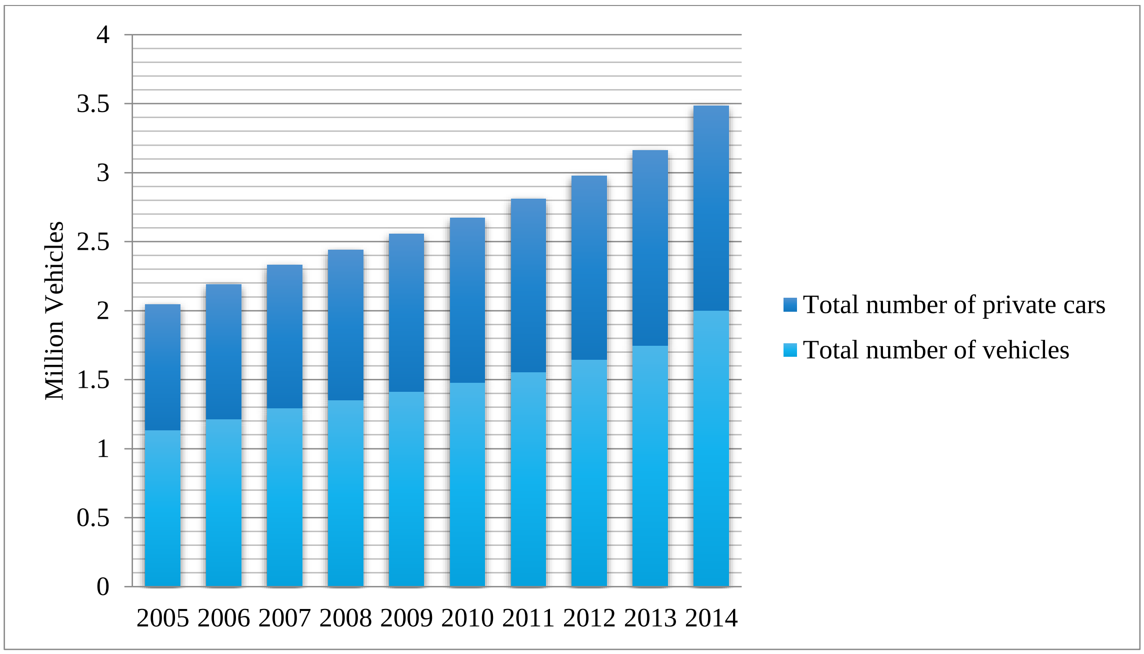


Figure 35. Total number of private cars compared to the total number of vehicles in Kuwait between 2005-2014, adapted from (CBS, 2015)

According to a World Bank Report (WBR, 2006), this car ownership average is higher than any other developed country, which is, on average, one car for every three residents. The CO_2 emitted from vehicles varies according to the fuel economy of the vehicle and carbon content of the fuel used. Due to the limited data about fuel economy and average distance traveled by Kuwait vehicles, a general estimation of CO_2 emitted from these vehicles was derived according to the total amount of gasoline and diesel sales each year by Kuwait fuel stations. This method is adopted from the US EPA (EPA, 2012). All gasoline and diesel consumed in Kuwait are derived from local refineries, except Euro4 Gasoline (95 Octane number), which is imported for ultra-deluxe cars (Table 13) (Appendix M). Since factories also consume diesel from fuel stations, the total amount of diesel sales was decreased by 20% to estimate CO_2 emitted from heavy vehicles. This percentage was determined following communications with engineers in KNPC. The EPA (2015) estimates that the emission factor of CO_2 emitted from gasoline is 0.00979 metric tons CO_2/ gallon while diesel emits 0.0112 t CO_2/ gallon. Table (13-14) illustrate both gasoline and diesel consumption in Kuwait gas stations from 2007 to 2016 and the anticipated CO_2 emissions in this period.

Table 13. Fuel sales in the local market between the years 2007-2013 were taken from (KNPC, 2016)

Fuel (million Gallon)	2007	2008	2009	2010	2011	2012	2013
Total Gasoline	802.316	831.983	850.792	881.409	904.498	944.837	990.222
Total Diesel	236.444	240.227	271.885	295.957	293.695	337.104	336.407

Table 14. Carbon dioxide emitted from gasoline and diesel consumption during the years 2008-2016 (Estimated consumption of fuel for years 2014 to 2016 were taken from (KNPC, 2016)

Carbon dioxide ($MtCO_2/y$) from	2008	2009	2010	2011	2012	2013	2014 (Est.)	2015 (Est.)	2016 (Est.)
Gasoline	8.145	8.329	8.629	8.855	9.249	9.694	10.153	10.634	11.665
Diesel	2.69	3.045	3.314	3.289	3.775	3.767	4.04	4.334	4.649
Total	10.835	11.374	11.943	12.144	13.025	13.462	14.193	14.968	16.314

Air transportation

Kuwait has one airport serving both regional and international travelers. It is able to handle more than 9 million passengers per year. The number of scheduled flights in Kuwait's airport increased by 224.5% during the period 2004 to 2014 (Director general of civil aviation, 2016).

Carbon dioxide emitted from any airport comes from a range of sources, including aircraft movement, transporting both passengers and cargo, and electricity consumption in the airport facilities. Due to a lack of robust data associated with direct and indirect CO_2 emissions from Kuwait Airport, a comparison was made between Kuwait Airport and Glasgow Airport (UK), which served a similar number of passengers (7.7 million). A study of Glasgow Airport (Bowe, et al., 2017) identified its emissions based on three sources that are considered in this study. The first source was the emissions obtained from the fuel consumed in company-owned vehicles (*e.g.*

refrigerators). The second was based on the emissions resulting from electricity consumption at the airport. It was excluded from this investigation to avoid double counting with power stations emissions. The third source considered was the uncontrolled emissions by the airport management (*e.g.* aircraft movement). In 2013, Glasgow Airport emitted 0.105 Mt CO_2/y. Following the same analysis, the anticipated CO_2 emissions from Kuwait International Airport would be 0.12 Mt CO_2/y.

Sea transportation

Kuwait has six ports; three designed for dry cargos, namely Shuwaikh, Shuaiba, and Doha (Figure 36), while the remaining three are crude oil terminals: Mina Al Ahmadi, Mina Al Shuaiba and Mina Al Abdullah (Figure 37). Shuwaikh port is the country's main commercial port, and it handles most non-petroleum cargo, whilst most of the crude oil and petrochemical products are exported through Mina Al-Ahmadi. The Kuwait Ports Authority (KPA) is responsible for operating all the commercial ports in addition to the new port that will be located on Boubyan Island, known as Boubyan port.

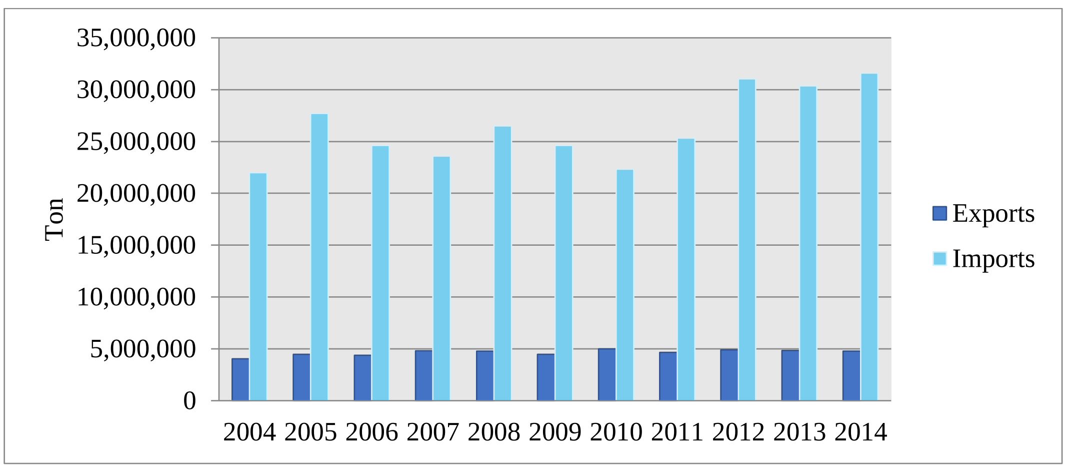


Figure 36. Imports and exports in all commercial ports in Kuwait, adapted from (CBS, 2015)

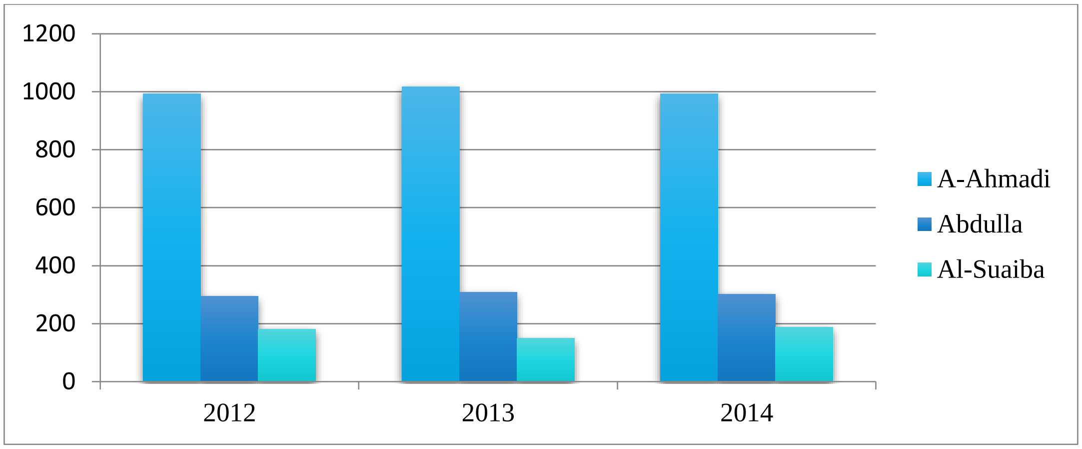


Figure 37. Oil Tankers Cleared from Kuwait Ports, adapted by the author from (CBS, 2015)

Merk (2014) clarified the main pollutants emitted from ports (Table 15) where CO_2 has the biggest share with 18 Mt. Containers and tankers are major contributors to this emissions level (85%) due to their dominant presence in terms of port calls, while Roll-on/Roll-off (Ro/Ro) ships have the lowest share.

Table 15. Estimated shipping emissions in ports (2011)

	Shipping emissions in ports (million metric ton)
CO_2	18.3
NO_x	0.4
SO_x	0.2
PM_{10}	0.03
$PM_{2.5}$	0.03
CO	0.03
CH_4	0.002

Source: (Merk, 2014)

A comparison was made between Gothenburg Port and Kuwait ports based on Twenty-foot Equivalent Units (TEU), which is the international unit used to estimate the cargo-carrying capacity of any port. Twenty-foot Equivalent Units (TEU) for Gothenburg Port in 2013 was 858,000, and the total associated CO_2 emissions were 0.16 Mt CO_2/y. The CO_2 obtained from electricity consumption was excluded from this analysis to avoid double counting. Based on a linear scaling out, the CO_2 emitted from all Kuwaiti ports with a total of 1,215,675 TEU is 0.2 Mt CO_2/y distributed across the three ports (Gothenburg Port Authority, 2016).

4.11 Forecast the CO_2 emissions of the State

As previously described, the Kuwait government aims to diversify its revenues and increase the non-oil contribution to 75% of the overall GDP (KFAS, 2017). Two main scenarios were developed to forecast the GDP through 2030 in the cases of the aim of the 'Kuwait plan' being achieved or not (Table 16). In scenario 1, Kuwait's GDP will totally rely on oil exports, as measured by oil-GDP, in the absence of any economic diversification. The oil-GDP was estimated based on the oil prices during the period 1990-2017 while the non-oil GDP was estimated based on a similar average proportion contribution during the same period. In scenario 2, the Kuwait government will succeed in diversifying its economy towards non-oil-based revenues and limits the oil-GDP to 25% of the overall GDP.

A linear regression model proposed by KEPA (KEPA, 2019b) was used to forecast the CO_2 emissions to 2030. The model was developed by using population and GDP data over the 1994-2016 period to figure the trends between these variables and CO_2 emissions.

$$CO_2e_t = 6.3E{+}03 + 0.018178*(P) + 3.17E{-}08*(GDP)_t \qquad (26)$$

Where:

CO_2e_t is the national CO_2 emissions in year t

P is the national population in year t

GDP is the Gross Domestic Product in nominal US dollars in year t

Two emission scenarios were developed; The Baseline Scenario which assumed the CO_2 emissions in the case of scenario 1 of the 'Kuwait plan' was dominant and the Diversification Scenario assumed the emissions in the case of the success of scenario 2 (Table 17). The total CO_2 emissions are projected to grow from 101 Mt in 2020 to 118 Mt in 2030, an average annual increase of about 1.68%, in the Baseline Scenario. Notably, the emissions showed a sharp increase in the diversification scenario during the same period from 102 Mt to 126 Mt, with an average annual increase of 2.35%, suggesting that economic diversification will have a negative impact on the carbon footprint of the state.

Table 16. The estimated GDP for the two modelling scenarios

	2015 GDP	2020 GDP		2025 GDP		2030 GDP		CAGR (2015-2030)	
Sectors	Actuals	Do Nothing	Desired	Do Nothing	Desired	Do Nothing	Desired	Do Nothing	Desired
Oil and Gas	14,875	15,436	15,436	17,774	17,774	20,371	20,371	2.1%	2.1%
Agriculture and Fishing	237	196	208	226	327	259	407	0.6%	3.7%
Manufacturing	2,312	2,612	2,832	3,008	5,280	3,447	6,790	2.7%	7.4%
Electricity, Gas and Water	1,090	923	1,144	1,063	1,538	1,218	2,037	0.7%	4.3%
Construction	1,003	892	1,104	1,027	1,698	1,177	2,309	1.1%	5.7%
Wholesale and Retail Trade	1,785	1,572	1,749	1,810	2,196	2,074	2,716	1.0%	2.8%
Restaurants and Hotels	408	341	548	393	914	450	1,198	0.7%	7.4%
Transport, Storage and Communications	2,505	2,439	2,749	2,809	3,974	3,219	5,093	1.7%	4.8%
Financial Institutions	3,450	3,196	3,416	3,680	4,337	4,218	5,432	1.3%	3.1%
Real Estate	3,380	3,201	3,414	3,686	4,455	4,225	5,772	1.5%	3.6%
Community, Social and Personal Services	8,527	7,799	8,884	8,980	8,980	10,293	14,939	1.5%	3.6%
Total	39,571	38,606	41,484	44,454	54,283	50,951	67,065	2%	3%

Source: (KFAS, 2017)

Table 17. The estimated CO_2 based on the forecasted GDP

	2020		2025		2030	
	Baseline scenario	Diversification scenario	Baseline scenario	Diversification scenario	Baseline scenario	Diversification scenario
GDP per capita (KD)	38,606	41,484	44,454	54,283	50,951	67,065
GDP per capita (USD)	126,241.6	135,652.7	145,364.6	177,505.4	166,609.8	219,302.6
GDP (Billion USD)	539	579	657	802	791	1041
Kuwait population (M)[a]	4.27		4.52		4.75	
CO_2 emission (Gg)	101,000	102,000	109,000	114,000	118,000	126,000
CO_2 emission (Mt)	101	102	109	114	118	126

a. (World Population Review, 2020)

4.12 Discussion

The carbon atlas of the state of Kuwait is summarized and presented in Table 18 (by category) and Figure 38 by subsectors and carbon load. Power plants were responsible for 42% of CO_2 emissions due to the high demand for electricity and water. Interrelated reasons are behind this demand, and they are summarized as the high level of electricity and water subsidization by the Kuwait government, the subtropical desert climate of the state and the significant growth rate of the Kuwait population. The power sector is typically considered the main source of carbon emissions worldwide (IPCC, 2007; Darwish, 2013; Darwish, and Darwish, 2008; Darwish, et al., 2008; Van Straelen, et al., 2010; Al-Salem, 2015; Gothenburg Port Authority, 2016) which is consistent with this study's findings. Chemical industries were ranked second in this analysis, followed by road transportation. It should also be noted that the carbon emissions from the petroleum industry in this work were related to all oil and gas activities stretching from upstream to basic chemicals production without double counting. This approach differentiates between the different individual carbon emissions loads of each industry in Kuwait which has not previously been undertaken. The chemical processes considered in this study included some products that may be accounted for as petrochemicals (*e.g.* polymeric products, basic feedstock gases, chemical off-gases, etc.). However, since a basic chemical industry exists in Kuwait that relies on petrochemical industries, double counting with those petrochemicals between these two sectors was avoided. In addition, the chemical industries assessed in this study also accounts for chemical products used as commodities (Table 18). Hence, this sector was suspected (and confirmed by this study) to be a major contributor to Kuwait's total carbon load (25.5%). By studying the results obtained in this work's carbon inventory and comparing countries emissions by rank (Li, et al., 2011), it is noted that Kuwait has a unique carbon emissions distribution due to the categorization of its industries. Since refining activities include the majority of AGR and sweetening processes, downstream activities include a significant share of the natural gas associated with carbon emissions. The paper market in Kuwait also contributes a substantial proportion of the carbon emissions (about one Mt CO_2/y) due to its reliance on petroleum-based feedstock and its GCC market share.

Table 18. Carbon footprint of the state of Kuwait 2016

Sector	Anticipated carbon dioxide emission ($MtCO_2/y$)
	2016
Air transportation	0.122
Aluminum	0.167
Sea transportation	0.226
Cement	0.322
Iron and Steel	0.312
Petroleum upstream processes	0.255
Petrochemical	2.642
Buildings	0.545
Petroleum downstream processes	8.962
Road transportation	16.314
Chemicals	25.45
Paper	1.0454
Power and Water stations	41.636
Total	98

Figure 39 depicts the geographical distribution of CO_2 stationary source emissions in the Shuaiba industrial area, about 50 km south of Kuwait City, which has the highest carbon footprint with 15 Mt CO_2/ y in 2013 followed by the Al-Zour area with 12 Mt CO_2/ y (Appendix N-V). The high footprint of the Shuaiba industrial area can be attributed to the presence of large-scale industrial activity (*e.g.* chemicals and petrochemical plants), Kuwait cement plant, North and South Shuaiba power plants, Shuaiba refinery (SHU) and many small industries. The area is also situated close to several new ventures in the chemical industries, including expansion in both the petrochemical and chemical sectors.

The Kuwaiti State total emissions have been published by both the World Bank 91.03 Mt CO_2/y (WBR, 2006) and IEA 69.82 Mt CO_2/y (IEA, 2010b) with corresponding differences of 7.7% and 40%, respectively. It is considered that since the process emissions have been covered in detail for the first time in this study, the higher value of the estimated CO_2 emissions in comparison with the other reported values is more representative. This result may demonstrate a systematic underestimation of CO_2 emissions from those states engaged significantly in the heavy process industries. Nevertheless, the level of detail and quantity of data provided in this work is significantly greater and should, therefore, supersede the two earlier analyses as the figure for the total Kuwaiti CO_2 emissions.

However, the differences do highlight the shortcomings of the simplified analysis previously published and demonstrate a need for similar work to be carried out for all national states as the potential margin for error appears to be within the same order of magnitude (i.e., tens of percentage points) as existing and on-going planned GHGs emissions mitigation targets. This outcome demonstrates that any benchmark of CO_2 emissions used as a reference point could be substantially incorrect, and the World Bank and IEA estimates should be utilized with great care.

Kuwait's government established two scenarios for its GDP for 2020, 2025, and 2030. If non-oil GDP contributes to 75% of the overall GDP, the total CO_2 emissions are estimated to be 126 Mt in 2030, otherwise, it will be 118 Mt.

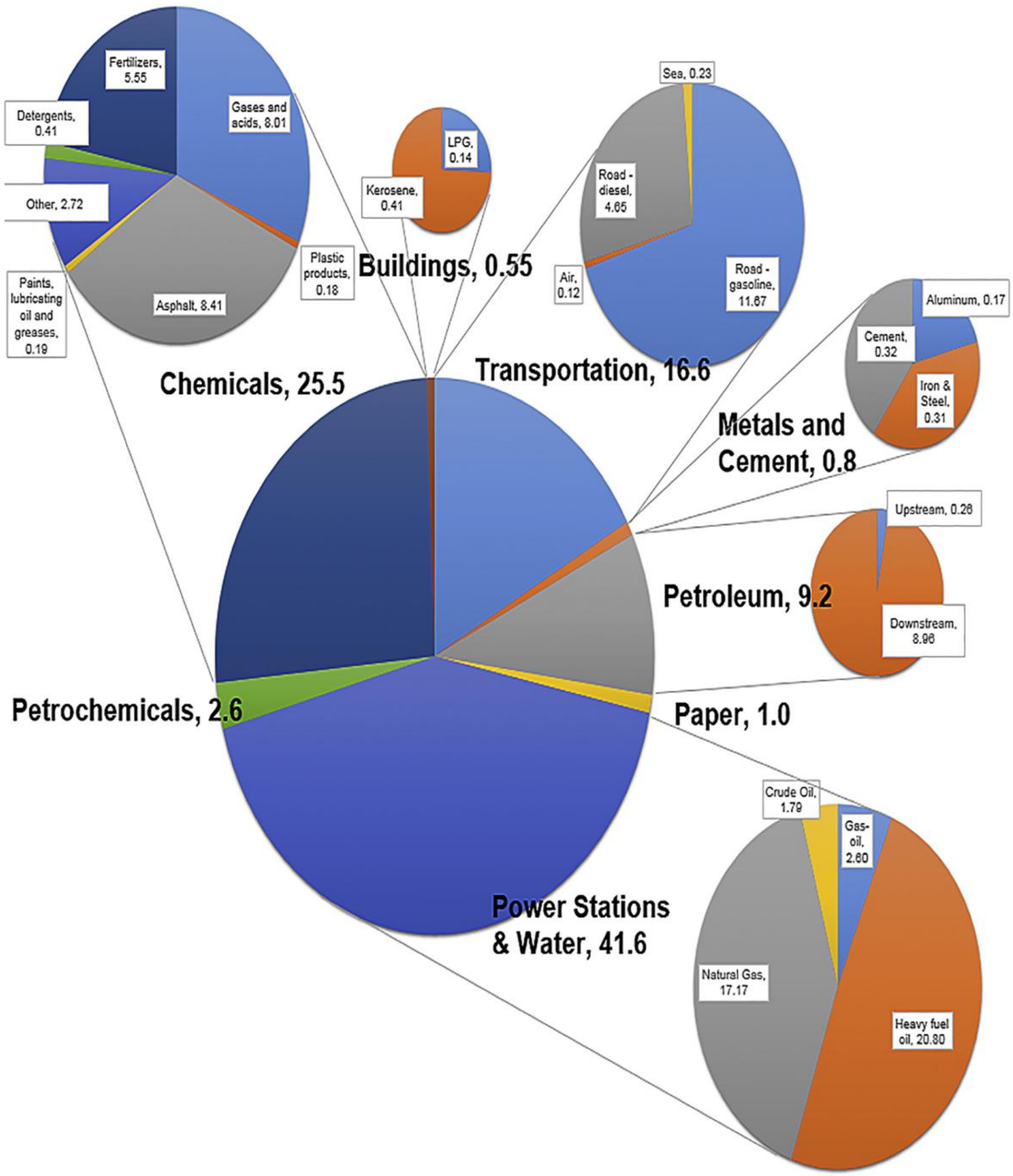


Figure 38. Carbon footprint of the state of Kuwait in 2016 Mt CO_2 /y

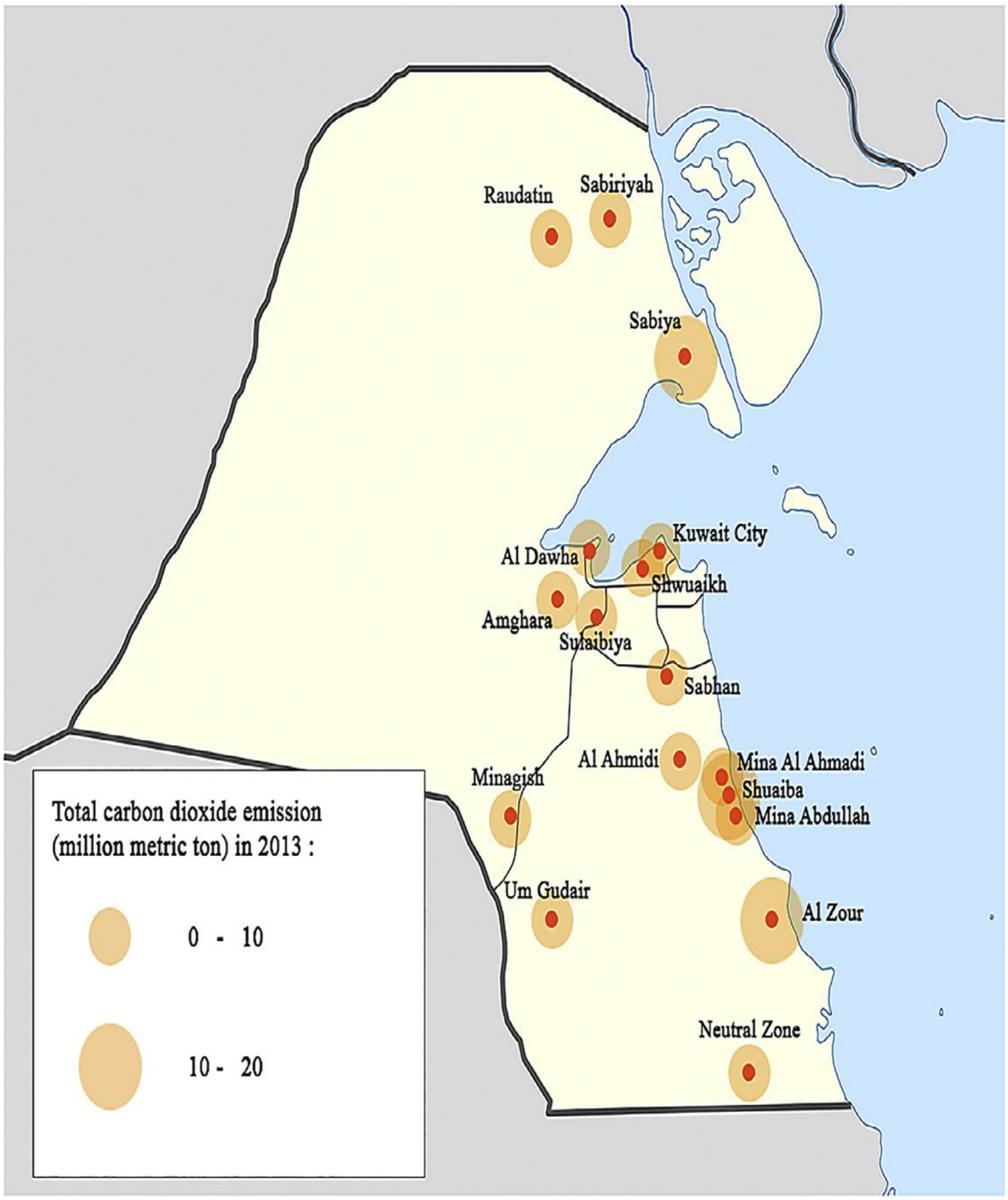


Figure 39. Geographical distribution of CO_2 emissions from stationary sources

Chapter 5: Strategic contexts for Carbon Capture in the State of Kuwait

5.1 Introduction

Carbon Capture Utilization, and Storage (CCUS) is a crucial enabling technology that supports delivery of the dual challenges of maintaining fossil fuel as a key source of energy whilst simultaneously dramatically reducing the associated CO_2 emissions. It has been extensively investigated in Western countries as an effective decarbonization strategy. However, there are limited, historical technical studies which analyse the potential of CCUS in fossil fuel dependent countries such as Kuwait. To bridge the existing knowledge gaps, this chapter scrutinizes the potential of deploying CCUS technologies in key Kuwaiti industrial sectors and storing CO_2 emissions, at a national level from both technical and economic perspectives.

5.2 Stakeholder attitude toward CCUS

5.2.1 Focus group discussion

The results of focus group discussions held in 2017 are shown in Figure 40. The main themes discussed are included alongside their frequency, shown as a percentage.

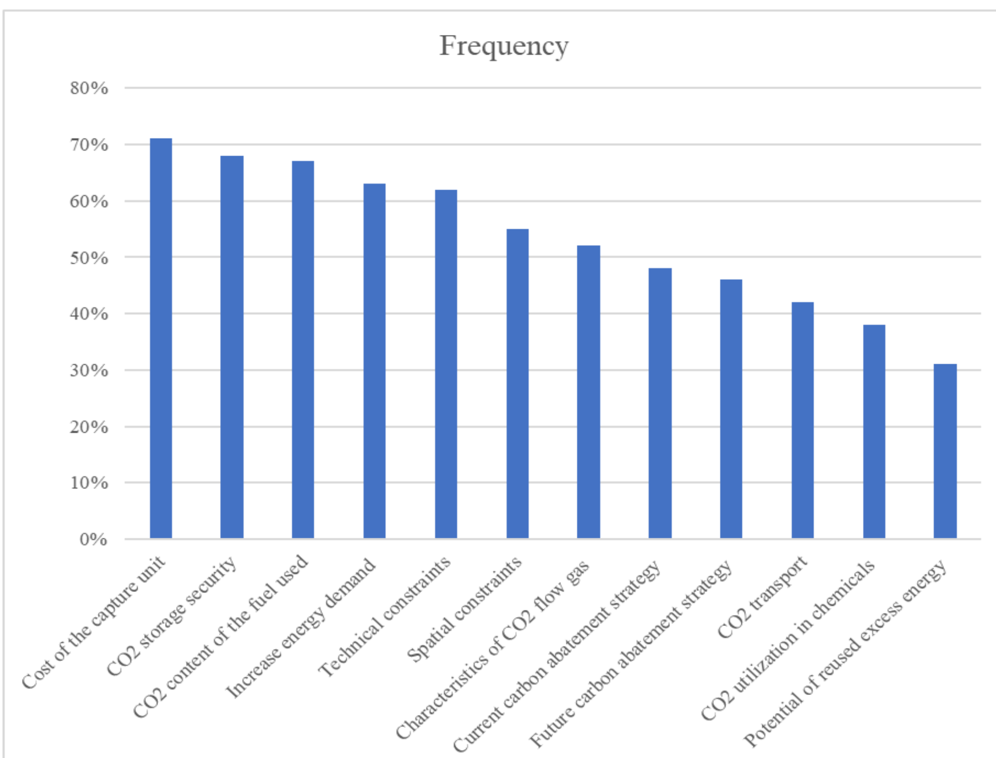


Figure 40. The frequency of the themes discussed in the group discussions

Based on the results, the most frequently mentioned factor when considering CCUS was the added cost and this comment was valid across all sectors, particularly for private companies as the additional costs could affect their ability to be competitive in both local and international markets. The second most frequently mentioned concern was the storage security and how to avoid any leakage to the surface or any neighboring freshwater aquifer. This was followed by technical themes regarding the CO_2 percent in the flowing gas and how this will impact the level of treatment required. Strongly held concerns were shared regarding the methods of providing the energy required for the captured units and the main modifications required in the production pathways. The energy concern was observed across all the groups but was a particular issue for MEW representatives due to the long hot summer where they usually experience a shortage of energy. Additionally, technical constraints were raised by delegates from the iron and cement groups since their facilities are not designed to be retrofitted with captured units. In general, there was a high level of uncertainty across all the groups regarding the potential of using CO_2 in chemical industries other than for EOR.

5.2.2 Information-Choice Questionnaire (ICQ)

The following section discusses the results of the Information-Choice Questionnaire (ICQ) related to current CO_2 abatement practices in Kuwait energy and non-energy sectors and the technical and economic issues associated with the potential future deployment of carbon capture technologies (Appendix W-Y).

Basic information

The first field of the questionnaire covered basic information and all stakeholders were asked five questions regarding the sector type, the pros of their current technology used, fuel type, main sources of energy, technical and space hurdles for introducing carbon capture facilities.

The three major sectors covered were energy production, petroleum downstream processes, and petroleum-based industries with around 74% share of participants (Figure 41). Then the cement industry and other manufacturing processes with 13%. The final group was the iron, paper, chemicals, and metal products sectors with 3.2% per sector resulting in a total of 12.8%.

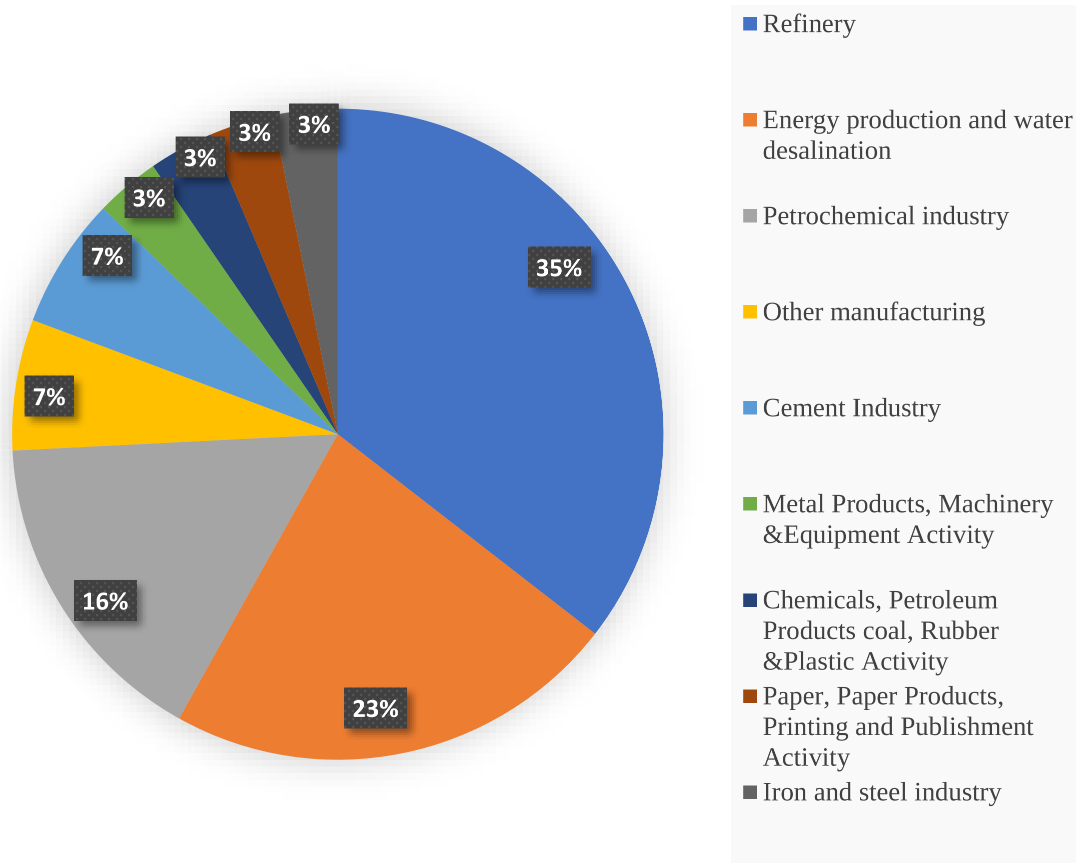


Figure 41. Response to interview question: What is the best description of the production process in your facility?

For the second question, all the stakeholders were asked to explain the advantage of the current technology used in their facilities. Most of the responses showed a preference for long-life technology with lower CO_2 emissions. In the third question, relating to the main sources of energy, natural gas and crude oil were equally used with 32% each while heavy fuel oil and coal have a considerable share with 29 and 7%, respectively. From Appendix X.2 and Y.2, heavy fuel oil and crude oil were dominant in energy and petroleum downstream processes with around 65% of energy sourced from these two. The high carbon content of the locally consumed fossil fuels confirms the need to introduce appropriate mitigation strategies in these facilities.

As shown in the Appendix W.4, approximately half of the responses indicated that boilers were the main sources of energy used in their facilities. Whilst in refineries, approximately half of the energy is sourced from a hydrogen plant (Appendix Y.3). Regarding spatial constraints, the results demonstrate that space is not a major issue with 48% of responses indicating that appropriate space can be allocated for the capture unit, particularly within the energy sector (Appendix W.5).

The carbon footprint

The second field within the questionnaire was designed to illustrate the main sources of CO_2 and the character of these sources. As shown in the Appendix W.6, a sizable portion of the stakeholders believed that heaters and process units have the largest share of CO_2 emissions, and slightly more than half of the respondents assumed that flowing gas contains less than 15% of CO_2 (Appendix W.7). With respect to partial pressure, more than 80% of energy stakeholders believe that the partial pressure of their flowing gas is between 100 to 1000 KPa (Appendix X.7) whilst 50% of stakeholders from other sectors believe that the partial pressure of flowing gas is between 100-1000 KPa (Appendix W.8).

Carbon dioxide abatement practices

Currently, most sectors face dual pressure either locally from KEPA or globally from the international markets to adopt sustainable production pathways. Because of this, the third section of the questionnaire aimed to evaluate the current and future CO_2 abatement practices.

Appendices (W.9 -W.10) illustrate the results of the current and future carbon abatement strategy adopted in these facilities. There is positive support for improving the efficiency of the current technologies used rather than switching to lower-carbon fuel. From the Appendix W.11, more than 60% of respondents consider CCUS to be a potentially critical technology in the event of the introduction of a carbon tax in the state.

Applicability of carbon capture technologies

The questionnaire's fourth section aimed to evaluate the realistic potential of CCUS technologies by considering the technical and spatial barriers of each carbon capture technique. Concerning post-combustion, all the stakeholders were asked about the units that produced excess energy which could be reused in a capture unit. The responses show that heaters were the main sources of excess energy in all sectors with 42% (Appendix W.12). In the case of energy and petroleum downstream sectors, the responses shown in Appendix X.11 and Appendix Y.11

demonstrate the stakeholders' belief in the ability of the process units to provide the required energy.

Regarding oxy-combustion, there was a strong consensus across all sectors that their facilities are technically able to operate in the oxy-fuel mode (Appendix W.13). Appendix W.14 shows a lack of agreement regarding the units that need to be modified for this purpose, heaters and process units received equal responses 43% and 44% respectively. When the stakeholders were asked about the technical potential of reusing part of the captured CO_2 in the generator to reduce the associated temperature, around half of the respondents lacked confidence about bypassing the captured CO_2 due to insufficient experience (Appendix W.15).

Appendix W.16 deals with different technical aspects associated with using hydrogen as the main fuel in pre-combustion technology. Slightly greater than one-third of respondents demonstrate positive support toward hydrogen compared to 11% who are still unconfident. In petrochemical industries, the internally produced H_2 is usually consumed in hydrocracking processes to upgrade the heavier petroleum fractions.

The difference in heat distribution between hydrogen and conventional fuel raises some technical concerns including fear of explosion and the need to upgrade the burners. However, several publications have addressed this issue through experimental analyses where the effects on heat, flow, and radiation distribution of process heaters, when replaced by hydrogen, are not significant (Weydahl, et al., 2013; Lowe, et al., 2011).

The risks associated with deploying carbon capture technologies

When asked what potential risks could arise from deploying a large-scale CCUS project, the majority of respondents raised concerns about the environmental risks, mainly leakages associated with the capture, transport, and storage of CO_2 (Appendix W.17). The other two major concerns are health and safety indicated by 28 and 24% of respondents, respectively.

Utilization pathways

The last section of the questionnaire dealt with utilizing the captured CO_2 as an effective way to reduce the net cost of the capture process. In response to the first question about the potential of reused CO_2 in their production pathway, the stakeholders were almost equally distributed between agreement and disagreement regarding inclusion, with 29 and 32%, respectively. Whilst the remaining third were not confident about how CO_2 can be integrated with their pathways (Appendix W.18).

Since injecting CO_2 in the decline oil and gas reservoirs are the most economically attractive utilization pathway, the second question focused on the potential for modifying their current pipeline to transport CO_2 for EOR reservoirs (Appendix W.19). In the refinery sector, more than half of respondents support the modification process (Appendix Y.18), compared to 29% in the other sectors.

Through the focus group discussion and the ICQ, most of the participants concerns were focused on the technical readiness of their facilities to work on carbon capture technology. Because of this, the second section aimed to address the knowledge gap regarding the technical performance of Kuwait's different sectors after introducing carbon capture units.

5.3 Potential Industrial CO_2 Capture in Kuwait

In Kuwait, CO_2 capture technology can be considered as an add-on for some industrial sectors where the low-pressure CO_2 steam can be utilized directly for electrical generation. Meanwhile, major technical modifications which affect the process life cycle are required for other sectors. The following sub-sections showcase the major carbon hotspots in Kuwait and detail how CO_2 emissions from individual sectors could be captured as well as outline the associated challenges.

Petroleum Refineries: refineries are an intense source of CO_2 emissions. They are responsible for 6% of global CO_2 stationary emissions, which is equivalent to one billion metric tonnes per year (Miracca, et al., 2013). In Kuwait, they represent over 9% of the national CO_2 emissions (Figure 38). Similar to other chemical industries, oil refineries are characterized according to their level of complexity and type of feedstock they process. They are often well distributed over a wide area with multiple sources of CO_2 emission, which increases the complexity of CCUS deployment.

A simplified analysis was carried out in this study by focussing on technologies capable of capturing CO_2 from the Process Unit Heaters (PUH), Fluid Catalytic Cracking (FCC), and Hydrogen Production (HP) units in petroleum refineries, which are the primary sources of CO_2 emission. Post-combustion and oxy-fuel capture techniques are the two most mature technologies that have the potential to be applied in the PUH.

Hurst (2005) recommended using a central location treatment unit to overcome the distribution problem of PUH (*e.g.* central gathering spot or hub). A large-diameter duct is required to collect and send the stack gases to a treatment location. Space availability for construction of this duct in complex refineries, which is the case in Kuwait, is one of the main challenges. Both nitrous oxides (NOx) and sulphur oxides (SOx) must be eliminated from the flue gas stream before the post-combustion CO_2 capture process. This is widely applied across various industries for environmental reasons. Furthermore, SOx emissions should not exceed 50 (ppm) to avoid the deactivation of the solvent in post-combustion capture (Metz, et al., 2005).

The main requirements considered in retrofitting PUH and boilers are twofold: the refinery's utility section and the waste/effluents sources. The former includes steam, cooling and process water while the latter encompasses amine-reclaimed waste units, Combined Heat and Power (CHP) stacks for additional power requirements, and cooling towers. These requirements were previously discussed by Hurst (2005) for the Grangemouth Refinery in the UK where 196,000 barrels of oil were processed per day and was able to reduce its carbon emissions by 2 Mtpa.

It is well established that the two possible carbon capture techniques that can be applied for FCC units, based on their characteristics, are post-combustion and oxyfuel combustion (De Mello, et al., 2009). To control the temperature of the combustion process in oxy-fuel combustion, some of the CO_2 is recycled back to the regenerator. However, the high concentration of CO_2 emitted from the HP unit makes it suitable for carbon sequestration. Carbon dioxide can be captured from three possible sources in this unit. They are: (1) the syngas stream where most carbon monoxide (CO) is converted into CO_2 in the shift converter; (2) the Pressure Swing Adsorption (PSA) unit with high purity hydrogen products; and (3) the hydrogen plant flue gas (Stockle and Bullen, 2008).

Cement Industry: the cement industry is a significant CO_2 emitter. It produced 1.8 Giga tonnes (Gt) of CO_2 in 2006, which was equivalent to 7% of global CO_2 emissions (Gao, et al., 2015). In 2016, it was responsible for 0.322 Mt of CO_2 emissions in Kuwait (Figure 38). A post-combustion process using amine scrubbing is the most commercially mature technique and most appropriate for the cement industry. A waste-heat recovery or CHP unit is typically used to provide the thermal energy required for the solvent regeneration process (Figure 42). Post-combustion capture has the advantage of being technically compatible with the existing cement plant in Kuwait at low technical risk with the full flexibility of being extensible for use with new plant installations (Li, et al., 2013).

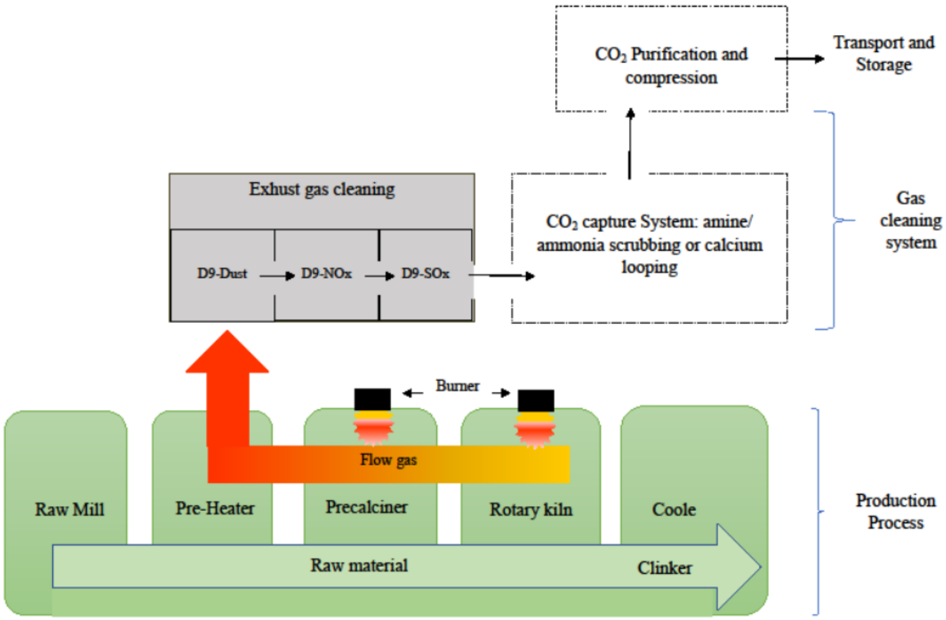


Figure 42. Generalized schematic for post-combustion technology applied at a cement plant. Figure adapted from (United Nations Industrial Development Organization, 2010)

This technology can typically eliminate around 80% of the carbon footprint in a cement's processing line (ZEP, 2013). The main technical barriers of retrofitting cement plants with post-combustion technology are summarised as follows (IEA, 2008a):

- The high concentration of SOx, nitrogen dioxide (NO_2) and dust affect the efficiency of the capture process.
- Excess electricity demand and process steam used symbiotically for CO_2 capture and compression processes; and
- The need for flue gas cooling equipment to maximise the efficiency of the capture process.

By applying the post-combustion technique to the Kuwait Cement Company's process plant, the total anticipated CO_2 emissions could be reduced by 80% to 0.0644 Mtpa. Oxy-fuel combustion is another cost-efficient CO_2 capture technique that can eliminate more than 90% of the carbon footprint of cement. However, all individual units in the cement plant will need to be modified to operate in a full oxy-fuel combustion mode. In this case, oxygen is isolated from the air and becomes the main oxidation reagent in the cement plant burner. Oxy-fuel combustion can take place in both the precalciner and cement clinker—the former performs the calcination process whilst the latter produces clinker brick. A Vacuum Pressure Swing Adsorption (VPSA) unit can then be used to purify the high concentration of CO_2 yielded from these two units.

To overcome the main technical barriers of full oxy-fuel combustion, partial oxy-fuel combustion can be deployed, in which only the preheaters and precalciner will be retrofitted. This technique could eliminate around 70% of CO_2 emitted from the cement plant (Hills, et al., 2016). Pre-combustion capture is not economically attractive in cement facilities where the bulk of CO_2 emissions does not come from the combustion of fossil fuels.

Iron, Steel, and Aluminium Industries: more than 2.5 Gt of annual CO_2 is emitted globally to the atmosphere from the iron and steel industries (Tsai, 2014), which is also responsible for 0.322 Mt/y of CO_2 in Kuwait. The main challenges of carbon capture in the iron and steel industries are the high impurities present in the gas streams, in addition to multiple CO_2 sources within the industries (*e.g.* BF, coke, stove, and power stations). The flow gas stream of a BF unit typically contains 17─25% of CO_2, 20─28% of CO, 1─5% of hydrogen (H_2) and 50─55% of nitrogen (N_2) (Rainer, et al., 2012).

Without making any modification to the BF structure, CO_2 can be captured directly from one of the two pathways: either from the BF gas stream or after a conversion process of CO to CO_2 downstream. Due to the lower concentration of CO_2 in the BF flue gas stream, the first approach has the maximum potential to eliminate CO_2 emissions by up to 50% compared to the second approach. The Top Gas Recycling Blast Furnace (TGRBF) is the most common technology used in the BF unit (as a modifying step) to increase its efficiency where the CO_2 capture technology can be coupled in a relatively straightforward manner. The European Ultra Low CO_2 Steel Making (ULCOS) program has defined this as a solution that has been realized at the commercial stage (Kuramochi, et al., 2012). The concentration of the emitted CO_2 from the TGRBF is around 35 vol.%, which is compatible with multiple carbon capture technologies (Figure 43). Both MEA and VPSA have been tested at pilot scale for this purpose (Danloy, et al., 2009).

Both modifications to the BF with carbon capture proved that CO_2 could be reduced by eliminating 45─55% of CO_2 emitted per tonne of crude steel production (ZEP, 2013). These technologies can be retrofitted to the conventional BF, which are currently deployed by Kuwaiti steel companies.

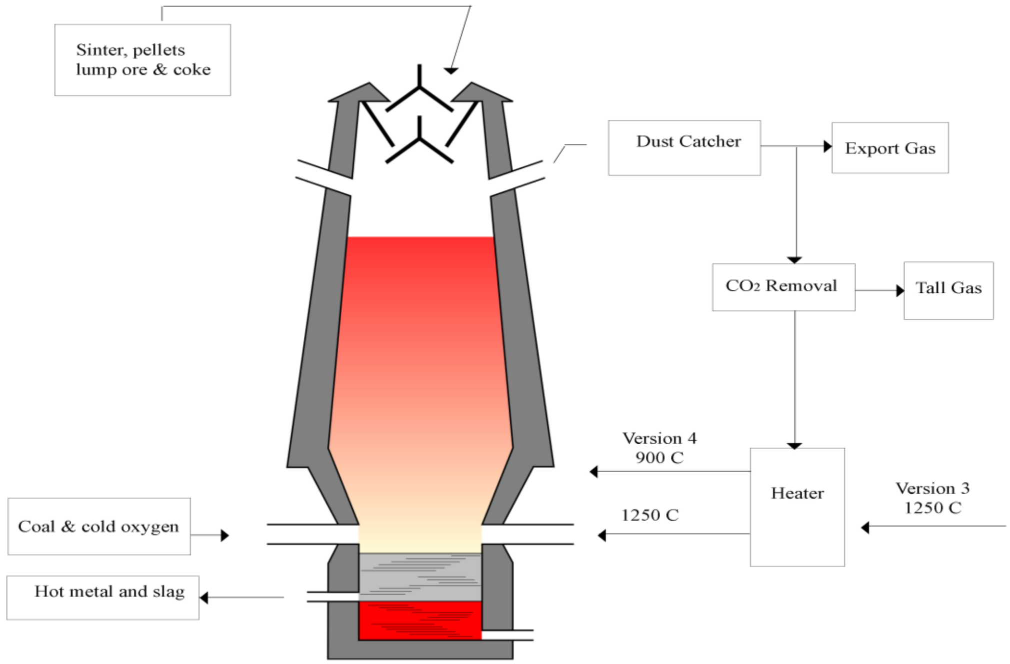


Figure 43. Basic diagram of a blast furnace equipped with TGR with capture, adapted from (United Nations Industrial Development Organization, 2010)

Capturing CO_2 from the DRI process has been used worldwide to enhance the quality of the fuel gas (Müller, et al., 2018). Applying carbon capture technologies to this unit is also considered more cost-effective when compared to the BF where the concentration of CO_2 is 25–35 vol.% (Kuramochi, et al., 2012).

Due to the economic growth in GCC countries after the discovery of oil, aluminium consumption has risen significantly during the past few decades. Kuwait relies largely on imported aluminium from western countries (Global Business Report, 2016). As such, the sector is only responsible for 0.17% of Kuwaiti CO_2 emissions (Figure 38), primarily from the smelting process. In contrast to the other industries, CO_2 emissions from aluminium production are generally not contaminated by impurities. However, the concentration is extremely low 1.2 vol.%, which makes its capture economically unattractive (Lassagne, et al., 2016). Therefore, the decarbonization of the aluminium sector in Kuwait is excluded from the analysis.

Chemical and Petrochemical Industries: chemical and petrochemicals are among the largest energy consumers in Kuwait. International Energy Agency (IEA, 2008c) reported that steam boilers and Combine Heat and Power (CHP) systems are the main sources of CO_2 emissions across these sectors. As the technical feasibility of retrofitting boilers with post-combustion has been presented in more detail in the petroleum refineries section, it is not further discussed here. In a CHP plant, the energy demand for post-combustion can vary significantly depending on the operational mode of the plant. Flue gas cooling, CO_2 regenerator condenser, and lean solvent cooling units are the three main sources that provide the low-grade heat used for solvent regeneration. According to Kvamsdal, et al. (2007), the ability of how to control the additional subsystems as well as recirculation and heat exchange streams would be the main operational challenge in retrofitting CHP plants with both oxy-fuel and pre-combustion capture technologies.

Power and Water Desalination Plant: more than one-third of anthropogenic CO_2 yields from the power sector (Olajire, 2010). In Kuwait, it is responsible for more than 40% of the carbon footprint (Figure 38). Water desalination units driven by fossil fuel combustion are also coupled with power stations. Various studies, for instance (Holden, 2014; Zhang, Liu, et al., 2012; and Cebrucean, et al., 2014) have addressed the feasibility of retrofitting conventional power generation plants with carbon capture technology. Abu-Zahra, et al. (2007) indicated that the net efficiency of conventional power plants could be reduced by up to 14% after integrating carbon capture technology, due to the excess steam produced by the carbon capture or compression processes. The location and the ambient conditions of Kuwaiti power plants determine the feasibility and the compatibility of each power plant with carbon capture technology.

To handle the diluted gas stream obtained from the combustion of fossil fuel in power plants, large scale equipment is required for effective post-combustion capture technology. By-passing the carbon capture system is one of the most effective ways to retrofit conventional power plants with post-combustion techniques (Markewitz and Bongartz, 2018). In this case, the low-pressure steam can be re-used again for electrical generation at peak times.

Oxy-fuel combustion has the potential to be applied in power generation where only CO_2 and steam will be produced. Steam can be separated from CO_2 through condensation. To examine the feasibility of oxy-fuel combustion in power generation, seventeen large scale projects have been initiated worldwide, including the Callide power plant in Australia (SCCS, 2015). Because coal presents a higher carbon footprint, there is a global endeavour to gradually convert coal-fired power plants into gas-fired plants. As such, gas-fired power plants have become the core of R&D in this area.

The GHG R&D program of the International Energy Agency (IEA) focuses largely on integrating new power plants with CCS technologies. Retrofitting existing power plants is economically favourable in some cases for the following reasons:

- Most of the existing power plants are designed for a long-life period, which usually exceeds 40 years. As a result, retrofitting existing power plants is more cost-effective.

- Replacing or maintaining existing assets is commonly used to extend the lives of profitable long running power plants to avoid the capital cost of a new construction project.

The energy demand for operating the carbon capture process will cause a significant reduction in power plant efficiency. According to Haines and Davison (2009), a 20–30% reduction in the system efficiency would be induced if CO_2 were continuously captured from the power plants. This issue can be overcome by improving the flexibility of power plants in two ways (i) turning off the capture process during the peak period i.e. June to September in Kuwait, as shown in Figure 44 and (ii) releasing the additional electrical energy for export. Table 19 give detailed overview of the options for the temporary increase of CCS plants power output based on Haines and Davison (2009) analysis.

Table 19. Options for temporary increase of CCS plant power output

Option	Extra CO_2 released	CO_2 still captured
Description of Option	Turn off capture to free up parasitic power for export	Temporary reduction in parasitic power consumption
Pre-combustion	Only solvent regeneration energy and CO_2 compression power could be saved. The gasification process itself is a major source of losses in preparing CO_2 for capture	Hydrogen storage can be used to decouple gasification and capture from power generation
Oxy combustion	Only CO_2 compression power could be saved unless plant can run at full capacity on air instead of oxygen	Not possible. Liquid oxygen can be stored but energy efficient use demands continued operation of ASU to make liquid nitrogen or air when LOX is retrieved from storage
Post combustion	Possible but LP steam turbine and generator would have to be sized to accept the extra LP steam which stopping solvent regeneration frees up.	Possible if large quantities of rich and lean solvent are stored. LP steam turbine and generator would have to be sized to accept the extra LP steam which stopping solvent regeneration frees up.

Source: (Haines and Davison, 2009)

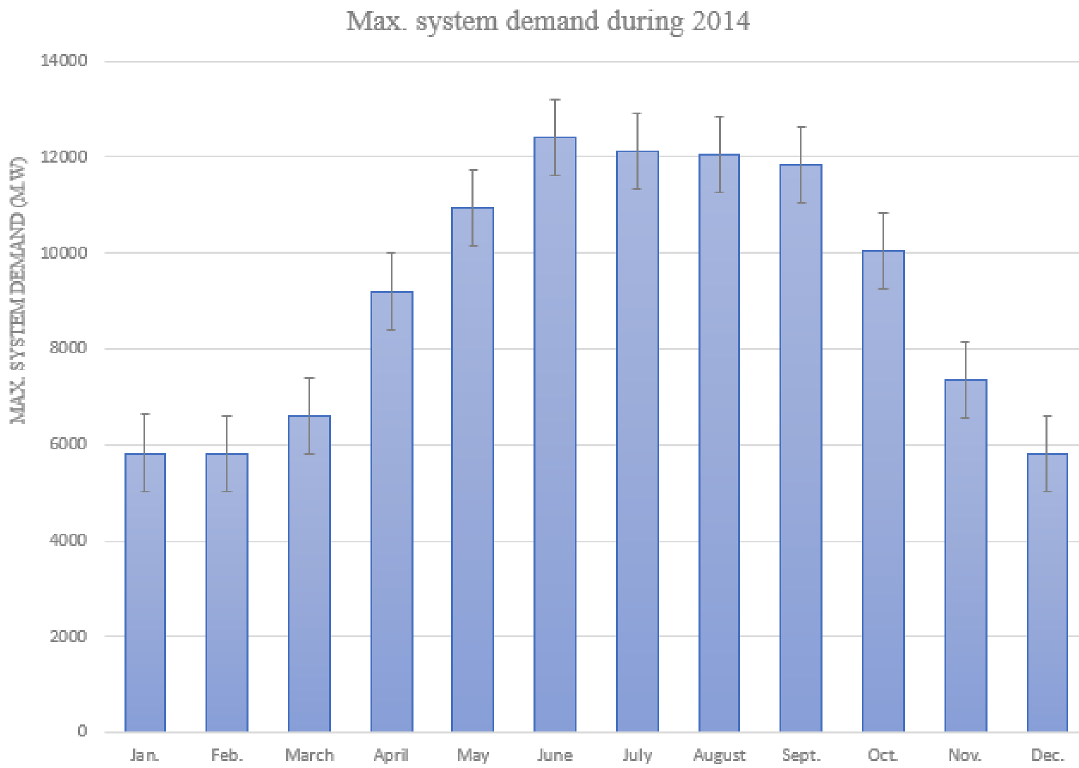


Figure 44. Maximum system load (M.W) during 2014, adapted from (CBS, 2015)

From a technical perspective, space availability in power plants required to accommodate new treatment units is one of the main barriers to retrofitting existing conventional CHP plants, such as those adopted in Kuwait. The required space ranges from 175 m x 150 m to 250 m x 150 m for natural gas pre- and post-combustion capture, respectively. Space is available for the capture units in four of the seven power plants in Kuwait. Table 20 gives a summary of the technical and modifications required to deploy carbon capture technology in energy and non-energy sectors.

Table 20. Summary of the technical and modifications required to deploy carbon capture technology in energy and non-energy sectors

Sectors	Units	Carbon Capture Technique	Technical and Spatial Barriers	Modification Required
Refineries	PUH	Post-combustion	- Space limitation for construction a large dimeter duct	- Retrofitting steam, cooling and process water in refinery's utility section - Introducing amine-reclaimed waste units
			- Presence of NOx and SOx	- Introduce Flue Gas Desulphurisation (FGD) unit to remove SOx - Introduce Selective Catalytic Reduction (SCR) to remove NOx
		Oxy-fuel combustion	Space limitation for Air Separation Unit (ASU)	Use a center location to treat the flue gas from all the units
	FCC	Post-combustion	High flue gas temperature	Some of the CO_2 is recycled back to the regenerator to control the temperature
		Oxy-fuel combustion		
	HP	- The high concentration of CO2 emitter makes it suitable for carbon sequestration. - CO_2 can capture from the syngas streams, PSA unit and the hydrogen plant flue gas		
Cements		Post-combustion	- Excess electricity demand - High flue gas temperature	- A waste-heat recovery or CHP unit is typically used to provide the thermal energy required - Introduce flue gas cooling equipment
		Oxy-fuel combustion	Units are not designed to work in the oxy-fuel mode	- All individual units need to be modified. - It can take place in precalciner and cement clinker
		Partial oxy-fuel combustion	Units are not designed to work in the oxy-fuel mode	Preheaters and precalciner need to be retrofitted

Table 20. Summary of the technical and modifications required to deploy carbon capture technology in energy and non-energy sectors, continued

Sectors	Units	Carbon Capture Technique	Technical and Spatial Barriers	Modification Required
Iron and Steel	BF	All carbon capture technologies	- High impurities in the gas streams - Multiple CO_2 sources (*e.g.* BF, coke, stove, and power stations)	Introducing TGRBF
Iron and Steel	DRI	Capturing CO_2 from DRI is more cost-effective when compared to the BF where the concentration of CO_2 is 25–35 (vol.%)		
Chemical and Petrochemical Industries	CHP	Post-combustion	High energy demand	Flue gas cooling, CO_2 regenerator condenser, and lean solvent cooling units are the three main sources that provide the low-grade heat used for solvent regeneration
		Oxy-fuel combustion	Technical issues associated with the additional subsystems, circulation and heat exchange streams	Control the additional subsystems as well as recirculation and heat exchange streams
		Pre-combustion		
Power and Water Desalination Plant		Post-combustion	Diluted gas stream	- Large scale equipment is required - By-passing the carbon capture system
		Oxy-fuel combustion		

In connection to pipeline transport and geological storage, there are limits for CO_2 purification.

Level of impurities in CO_2 stream from the power source: for both pipeline transport and geological storage, there are various limits for CO_2 purification. Impurities exist in the CO_2 stream that yields from each carbon capture technique and is obtained from three main sources; fuel oxidation, excess oxidant/ air ingress, and process fluids (Porter, et al., 2015). The impacts of impurities that exist in the CO_2 stream can generally be classified into chemical impacts, physical impacts, and toxic/ ecotoxic effects.

Impurities arising from different combustion capture modes

Oxy-fuel combustion capture impurities: various ranges of CO_2 purity are yielded from oxyfuel combustion according to the selected purification strategy. Flue gas stream obtained from oxy-fuel combustion usually contains certain levels of impurities (*e.g.* O_2, N_2, and Ar) that are yielded from combustion by-products and inert components. The percent of SO_x and Hg need to be strictly controlled to eliminate the corrosion concerned.

The demand for impurities removal, in this case, will be affected by certain factors, including corrosivity, transport, and storage economics, regulations, process requirements, toxicity, and constraints on geological storage (Porter, et al., 2015). To eliminate oxidation of hydrocarbon and aerobic bacterial growth, the level of oxygen in the CO_2 stream using Enhanced Oil Recovery (EOR), should not exceed 100 ppm.

Pre-combustion capture impurities: CO_2 streams obtained from pre-combustion capture techniques are greatly affected by syngas production and water gas shift reaction processes. Fuel composition, specifically sulfur content, will also have a significant impact on the CO_2 stream. Syngas composition will be affected by operation conditions (*e.g.* temperature) that will end up affecting the CO_2 quality stream.

Post-combustion capture impurities: in comparison to oxy-fuel combustion, post-combustion usually has a low level of impurities and N_2, water, and O_2 are the main ones. To get the CO_2 purification limit for geological storage purposes, Lee, et al. (2009) emphasized that Flue Gas Desulfurization (FGD) followed by Absorption by MEA, are the most favorable techniques to reach these standards.

5.4 Potential Industrial CO_2 Utilization in Kuwait

Industrial Emissions Hubs and Cluster: Carbon Capture, Utilization, and Storage (CCUS) has been widely used in various industrial facilities. These facilities have enormous potential to reduce the total cost of carbon capture chains that are employed i.e., by connecting industrial CO_2 sources to form an emissions 'hub', which is the building block of integrated industrial carbon 'clusters'. Combining industrial clusters for CO_2 emissions needs to be carefully considered because the composition and pressure of flow gas vary significantly from one facility to another (Table 21).

Table 21. Carbon dioxide stream of varying concentration and partial pressure of varies processes

Process	Sector	CO_2 purity (by volume)	Typical stream pressure (kPa)	Typical partial pressure (kPa)
Ethylene oxide	Chemicals	100%	2500	2500
Fermentation	Biofuels	100%	100	100
Cement kiln (oxy fuel)	Cement	> 90%	100	95
Oxy-fuel and chemical looping with coal	Power	80-98%	100	90
Direct reduce iron	Iron and steel	20-96%	100 to 500	Uncertain
Integrated gasification combined cycle (oxy fuel)	Power	20-40%	2000 to 7000	500 to 3000
Acid gas clean-up	Gas processing	2-65%	900 to 8000	20 to 5000
Blast furnace gas (top gas recycling)	Iron and steel	60-75%	100	60 to 75
Ethylene production	Chemicals	8-18%	2800	200 to 500
Hydrogen production	Chemicals (ammonia, methanol etc.), refining	15-20%	2200 to 2700	300 to 550
IGCC (air blown)	Power	12-14%	2000 to 7000	250 to 1000
Blast furnace gas	Iron and steel	14-33%	100	14 to 33
Cement kiln (air fired)	Cement	14-40%	100	14 to 40
Pulverised coal	Power	12-14%	100	12 to 14
Process heaters	Refining, chemicals	3-13%	100	3 to 13
Gas boiler	Power	7-10%	100	7 to 10
Gas turbine	Power	3%	100	3

Source: (IEA, 2013a)

Each industrial area has been studied as detailed in Chapter 4 and accounted for in this analysis as a potential carbon cluster. The most significant emissions cluster in Kuwait is Al-Shuaiba Industrial Area, which was established in 1964. The area is located on the coast, around 50 km south of Kuwait City. Carbon dioxide emitted from this area is related to both energy and non-energy emission sources where Shuaiba Refinery and Petrochemical Industries Company are based (Table 22). Most of the small industries in this area deal with diluted flue gases. These small industries could form an industry cluster as their total CO_2 emissions can reach significant levels. Electricity and heat demand for different capture techniques can be supplied by excess heat available in the facilities by using heat pumps or external units.

Table 22. Main CO_2 main sources in Al-Shuaiba Industrial Area and their respective annual CO_2 emissions

Company name	Plant type	CO_2 produced (Mt/year)	Percent of sharing in CO_2 emission
Abdul Aziz Abd Almohsen Al-Rashid Sons Factory	Paint	0.00225	0.0148
Al-Sharhan Aerosol Establishment	Detergents	9.88×10^{-6}	0.0000652
Kuwait national lubricating oil company	Lubricant oil	0.00473	0.0312
Kuwait lubricant oil company	Lubricant oil	0.0193	0.127
Kuwait Dana for oil company	Lubricant oil	0.0476	0.314
Chemkuwait for chemical industries	Inorganic acid	0.00622	0.041
Petrochemical industries company	Fertilizers	6.943	45.828
Al-Mubrouk Perfumes	Perfume	0.000247	0.00163
Tabahly Factory for perfumes	Perfume	0.000017	0.00011
National sponge factory and bed health	Sponge	0.0258	0.17
Shuaiba refinery (SHU)	Refinery	3.22	21.254
Shuaiba refinery terminals	Terminals	0.019	0.125
United Steel Company	Steel	0.197	1.3
Kuwait cement company	Cement	0.322	2.125
Shuaiba Port	Port	0.0896	0.591
North Shuaiba power plant	Power Plant	1.802	11.894
South Shuaiba power plant	Power Plant	2.480	16.369
Total		**15.15**	

There is only one source of high CO_2 emissions in the Al-Zour Industrial Area, i.e., South Al-Zour Power Station. The high carbon content of the fuel in this power station is the main cause of intense CO_2 emissions, which can be captured and utilized directly on site if local CCUS facilities were available. This area is hosting the ongoing New Refinery Project (NRP) known as the Al-Zour Refinery, which aims to satisfy the world's market demand of ultra-low sulphur diesel fuel, jet fuel, kerosene and naphtha (Al-Salem, 2015).

The configuration of the carbon capture and compression network can be designed in various scenarios. The selection of the optimum scenario is affected by interrelated factors, including capital cost, space availability and the level of maturity of the technologies applied. In addition to local treatment in decentralized carbon capture treatment units (as previously described), flue gas can be collected from all the facilities and treated in a central location. The scale of the carbon capture utilities depends on the volume of the flue gas and the degree of its impurities, which furthermore affects the infrastructure required for handling different flow gas characteristics, for instance, high- and low-pressure CO_2 as well as CO_2-rich and CO_2-lean amine. Two central treatment locations, which are 16000 m x 650 m in Al-Zour Industrial Area and 3000 m × 600 m in Northwest Shuaiba, within close proximity to the two highest CO_2 sources, are proposed for Shuaiba Industrial Area. Two mature carbon capture routes have been recommended for this configuration, which is post-combustion using MEA and oxy-fuel combustion using cryogenic oxygen production.

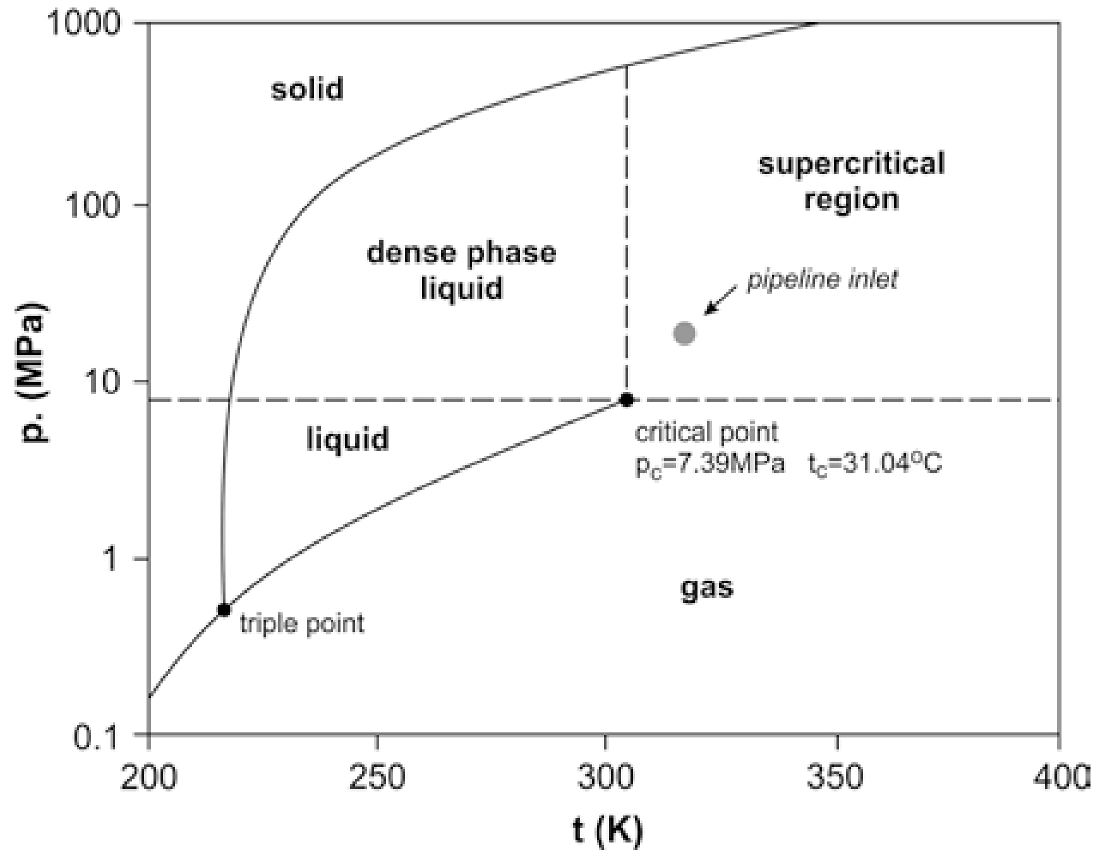
5.5 Potential of Using Hydrocarbon Pipelines and Industrial Infrastructure for CO_2 Transportation in Kuwait

After capturing CO_2, a significant CO_2 reduction can be realized when the purified CO_2 stream is compressed and transported through pipelines for utilization (Figure 45). This is considered the second energy-intensive process in a CCUS chain. The level of impurities associated with each carbon capture technique needs careful consideration when designing CO_2 compression systems. Reliable, safe, and economically feasible systems are required to transport CO_2 through pipelines in the form of liquid, gas, or two-phase flow. Transporting CO_2 in its liquid phase will only be economically feasible for short distances due to the need for pipelines which have large diameters. Compressors, which are mainly made of stainless steel to avoid corrosion, also contribute to the cost. The development of large-scale CCUS systems in Kuwait can be facilitated by taking advantage of the existing high-pressure pipelines used to transport natural gas. Whilst most existing pipelines are made of carbon steel, which is metallurgically suitable for CO_2 transportation, the design pressure of natural gas pipelines ranging between 60 and 80 bars may result in a lower transport capacity (Joana, et al., 2011). To evaluate how safe it is to reuse the pipelines for different purposes, an assessment is required on the life cycle history of pipelines. The assessment should cover design, operation, and maintenance processes, followed by conducting (i) simulation on the toughness of the pipelines and coating materials; and (ii) pressure tests to accommodate supercritical CO_2.

The impact of CO_2 flow gas impurities, which vary considerably with fuel types and capture processes, and their implications should be taken into consideration. Generally, CO_2 can be utilized in two ways:

- Fixing CO_2 to chemicals (*e.g.* urea) or fuels (*e.g.* methanol) through carboxylation or reduction; and
- Using CO_2 in its supercritical state without any modification reaction as in EOR.

For industrial areas without hydrocarbon infrastructure or suitable pipelines, the limitation of adequate space to develop this network may become a potential challenge.



Source: (Witkowski, et al., 2015)

Figure 45. A phase diagram for CO_2

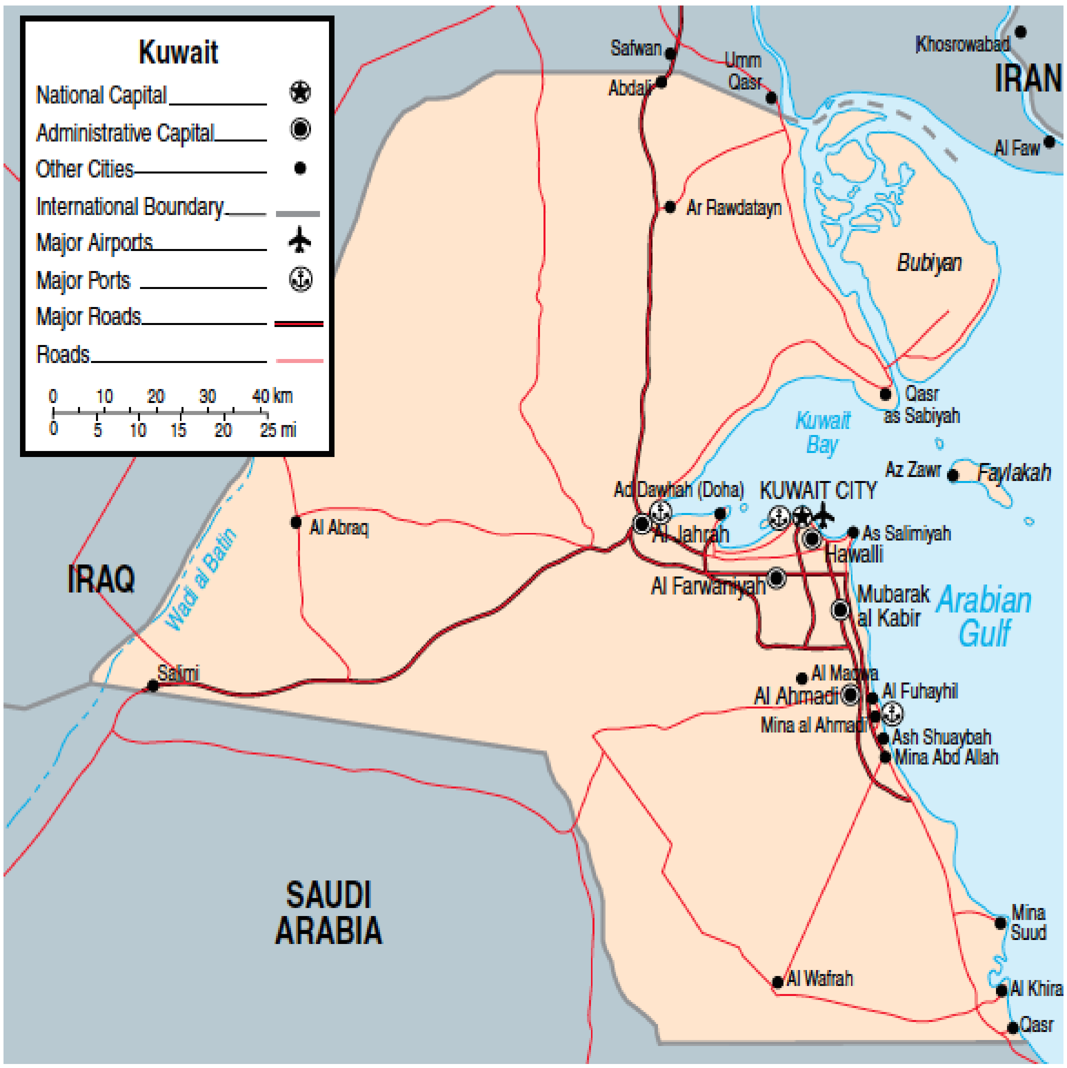
5.6 Planning Pipeline Routes

Carbon dioxide clusters and storage locations will determine the overall system design. The selected route of the CO_2 pipeline will affect the size (length and diameter) of the pipe, in addition to the location of assisted facilities such as booster stations.

Urban area: selecting pathway scenarios across urban areas represents additional challenges from various perspectives, such as safety procedures, that will lead to add an additional construction cost. The urban areas in Kuwait are located on the coastal plain south of Kuwait Bay, where Kuwait City is considered one of the highest density capital cities in the world. Only the pathway from the potential cluster areas to the Medina oilfield cross this high intense area.

Existing pipeline corridor: when selecting the CO_2 pipeline pathway, it is recommended to follow existing pipeline trajectories, which could reduce the total construction cost.

Obstacles: the number and location of obstacles which exist in the selected pathway, such as roads, will add additional challenges to the construction process. Despite the presence of certain techniques in designing a process to overcome this problem, this will lead to a rise in the total construction cost. Figure 46 illustrates the main and the secondary roads that exist in Kuwait, and it noted that there are no major interconnections between these roads and the suggested pathways.



Source: (Public Intelligence, 2017)

Figure 46. Existing major transportation modes in Kuwait

Protected Areas: some areas with a special interest, such as the protected areas dedicated to achieving long-term conservation zones for wildlife. These areas cover 1% of the total surface in Kuwait, as shown in Figure 47, and it is comprised of wildlife nature reserves, marine parks, scientific reserves, and others. The recommended pathways from the south to the north of the state will cross one of the main protected areas known as Al-Jdailleih protected area.

Source: (Al-Mudh'hi, 2012)

Figure 47. Protected areas in Kuwait

5.7 Potential of CO_2 Utilization in Enhanced Oil Recovery (EOR)

CO_2-EOR and CCS: hydrocarbon recovered from its natural reservoir through primary and secondary recoveries (Figure 48). Natural driving mechanisms (*e.g.* rock and liquid expansion drive, depletion drive, gas cap drive, water drive, gravity drainage drive, and combination drive) are the driving force of the primary recovery. These mechanisms will vary from one reservoir to another due to the uniqueness of every single reservoir. Satter, et al. (2008) emphasize that primary recovery is not able to produce more than 40% of the original hydrocarbons. The remaining hydrocarbon is produced by using artificial energy in secondary hydrocarbon recovery. This artificial energy can be either water or gas, which is introduced from one wellbore to

produce hydrocarbon from another wellbore. This fluid must have certain characteristics to accomplish the goal of the process, and they can be summarized into (Green and Willhite, 1998); ability to enhance the natural energy in the depleted reservoirs and ability to create conditions that are favorable for residual oil recovery through interaction with the reservoir's rocks.

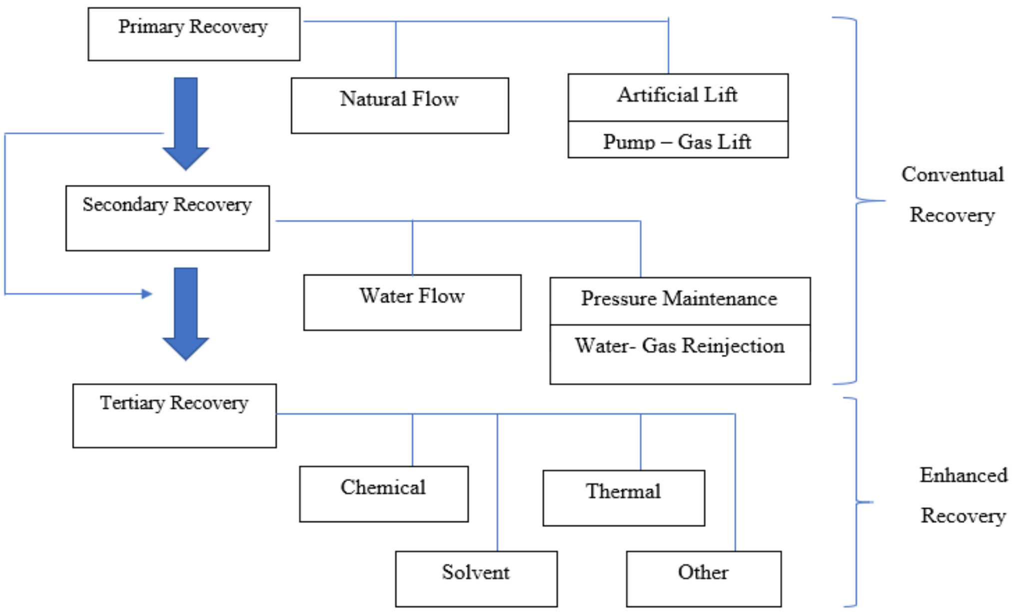


Figure 48. Typical recovery mechanisms during oil production adapted from (Bachu, 2016)

The EOR process can generally be a function of either microscopic or macroscopic displacement efficiency or a combination of them. As the name implies, microscopic efficiency occurs at a pore-scale where it measures the effectiveness of displacing fluid in moving the contact oil. The rule of displacing fluids on the entire reservoir can also estimate at a volumetric sense, which is known as macroscopic displacement efficiency.

The demand for CO_2 in the CO_2-EOR project will be varied along with the field life (Godec, et al., 2011).

The Enhancement process starts with the flushing of the depleted oil field with a considerable amount of CO_2. The effect of this process will not be observed until 18 to 24 months after the initial injection of CO_2.

- More crude oil is expected to be produced if more CO_2 is injected into the reservoir, until it reaches optimum production.
- Carbon dioxide will be produced in association with crude oil after certain injection times. This CO_2 will be recycled through re-injection into the oil field.
- The potential of the oil field to CO_2-EOR can be affected by the combination of specific characteristics, namely percentage of the remaining hydrocarbon in the oil field and the specific gravity of the hydrocarbon. Additionally, temperature, depth, heterogeneity, and permeability of the bearing formation can also affect the potential (Dooley, et al., 2011).
- There are specific requirements for using CO_2-EOR for climate mitigation that differentiates from directly injecting to enhance oil recovery. These requirements cover pre-injecting activities, co-injection, and post-injection activities.

CO_2-EOR and CCS: before embarking on an analysis of the potential of CO_2-EOR in the state of Kuwait, it's important to distinguish between CO_2-EOR and CCS. CO_2-EOR is one of the techniques used in tertiary recovery through the injection of CO_2 in the depleted oilfield to enhance the production of the remaining oil after primary and secondary recoveries. Only the U.S and Canada have applied CO_2-EOR on a large scale. In 2008, the U.S produced more than 250,000 barrels of crude oil through using CO_2-EOR (Oil and Gas Journal, 2008). Carbon Capture and Storage (CCS) aims to isolate CO_2 from its emission sources and keep it in deep subsurface to eliminate the side effect of this gas on climate change phenomena. Coupling CCS with CO_2-EOR also seems like an attractive option to yield the objectives of both techniques. Globally, only the Dakota Gasification-Weyburn CCS project employs CO_2-EOR. The demand for additional injection and production infrastructure increases the complexity of the CO_2-EOR project, which shows the main barriers to deploying this technique on a large scale.

State of the art CO_2-EOR technology: Godec, et al. (2011) assert the main five characteristics of state-of-the-art CO_2-EOR technology:

- Precise CO_2-EOR monitoring to make sure that CO_2 is not leaking from high permeability streaks in the oilfield.
- The volume of the injected CO_2 is raised from 0.4 Hydrocarbon Pore Volume (HCPV) to 1.0 HCPV.
- Choosing space between the wells within an appropriate distance.
- Introduction of WAG process.

- Assure that the minimum miscibility pressure will be maintained through the reservoir.

Next generation CO_2-EOR: next-generation CO_2-EOR technologies have been developed to overcome the main shortages of state-of-the-art technologies. These techniques are helped to further enhance oil production and utilize more CO_2, and they covered:

- Further increasing the injected CO_2 volume from 1 HCPV to 1.5 HCPV.
- Optimizing the placement and the design of the wells to have additional contact between the CO_2 and the oil.
- Improving the efficiency of oil recovery through increasing the miscibility range.
- Increasing the viscosity of the injected water by increasing the mobility ratio between CO_2/water.

It is worth mentioning that these techniques have been deployed, at least at pilot stage, but due to their prohibitive cost they are not yet economically attractive.

5.8 Potential of CO_2-EOR Projects in Arab World

In the Arab world, the current utilization of CO_2 is not exceeding industrial purposes (*e.g.* food processing). Ringrose, et al. (2013) illustrate that the single large-scale project of CCUS in the Arab world is operating in Algeria, where 1.2 Mt of CO_2 is captured annually from natural gas processes. Most of the oilfields in the region are now exceeding their primary production level, and there is a demand for secondary, and tertiary recoveries to obtain the remaining oil. Algharaib (2013) investigated the potential of over 107 Middle Eastern oil reservoirs for CO_2-EOR. The selected criteria for screening oilfields were based on extensive experience in this area. The analysis shows a high potential of these reservoirs in storing a considerable amount of the local CO_2 emitted.

United Arab Emirates (UAE): one of the major decarbonization strategies adopted by GCC countries, is in the United Arab Emirates (UAE), specifically Abu Dhabi. This strategy aims to capture almost 90% of the existing and future emission sources. United Arab Emirates (UAE) will run the first large scale CCS project from the iron and steel industry in the world. This project will capture 0.8 Mt of CO_2 per year from Emirate steel then transport it to the Rumaitha oil field for the EOR purpose.

Kingdom of Saudi Arabia: similarly, the Kingdom of Saudi Arabia has started to develop a series of strategies to use CO_2 in EOR operations in mostly depleted oil fields. Capturing around

0.8 Mt annually from Hawiyah NGL (Natural Gas Liquid) to Ghawar oil field is the first large scale project operated in the country. The project aims to evaluate all the risks and uncertainties associated with the process, including the migration path of CO_2 inside the reservoir.

5.9 Potential Application of CO_2-EOR in Kuwait

Kuwait is among the top oil producers in the world, and it has an excellent opportunity to remain in this position through using EOR development techniques (Alajmi, et al., 2015). Table 23 demonstrates the main reasons for the significant potential of deploying CO_2-EOR technology in the state.

Table 23. Reasons for deploying CO_2-EOR in the state of Kuwait

Why CO_2-EOR in Kuwait?	
	Presence of large CO_2 emission sources from both industrial and power sectors
	Short transport distance between the high emission sources and depleted oil fields
	Extensive knowledge in the oil and gas industry
	Development of large scale mega projects
	Existing natural gas infrastructure that can be modified in the future to use for transporting CO_2

Kuwait experience in the oil and gas industry adds an advantage to success in any CO_2-EOR projects. It started over a century ago, specifically in 1913 when the surface leak of oil was recorded in Bahra and Burgan (MO, 2018). After this, several geological surveys were conducted in 1917, 1924, 1934, until 1937 when the first exploratory well was drilled in Bahra. However, the quantity of crude oil did not reach a commercial level, which redirects all the attention for the Burgan region. After nine years, Kuwait started the commercial shipment from the Burgan oil field by exporting 16 thousand barrels per day. Following Burgan, the exploration operation extended, leading to the discovery of Magwa in 1951 and Raudhatain in 1955. In 1981, KOC developed its technologies with a 2D seismic survey for both on-shore and off-shore regions. In 1995, KOC covered the whole land area, Bubiyan island, and Saudi–Kuwaiti neutral zone with 4D seismic data that extended from analyzing the stratigraphic interpretations to studying the fluid movement within the reservoir (KOC, 2008).

Currently, Kuwait has ten intense CO_2 sources from power plants, and refineries that are located around 200 km from the north, and southern oil fields with two cluster areas could be made. The high carbon contents of the fuel used in Kuwait power plants will raise the purification requirements to meet EOR criteria while the pure stream from hydrogen production units can be used for EOR applications with no further treatment.

All the sources are concentrated along the coastal area and are responsible for half of the carbon footprint of the state (Section 5.4). This geographical distribution creates a potential for developing a cost-effective CO_2 infrastructure pipeline. In addition, Kuwait can reuse the existing natural gas infrastructure, after technical modifications, for CO_2 transferring as discussed in Section 5.5.

Furthermore, the Kuwait government is adopting the Kuwait national development plan, branded as New Kuwait that aims to transfer the country to become a financial hub in the region by 2035 (KEPA, 2019b) (Figure 49). It is designed around five themes, and seven pillars cover 164 strategic programs, projects, and initiatives. All these projects will add additional stationary sources in future years. In selecting the CO_2 source, several criteria should be taken into consideration including source type, CO_2 percent, flow gas pressure and temperature (Usman, et al., 2014).

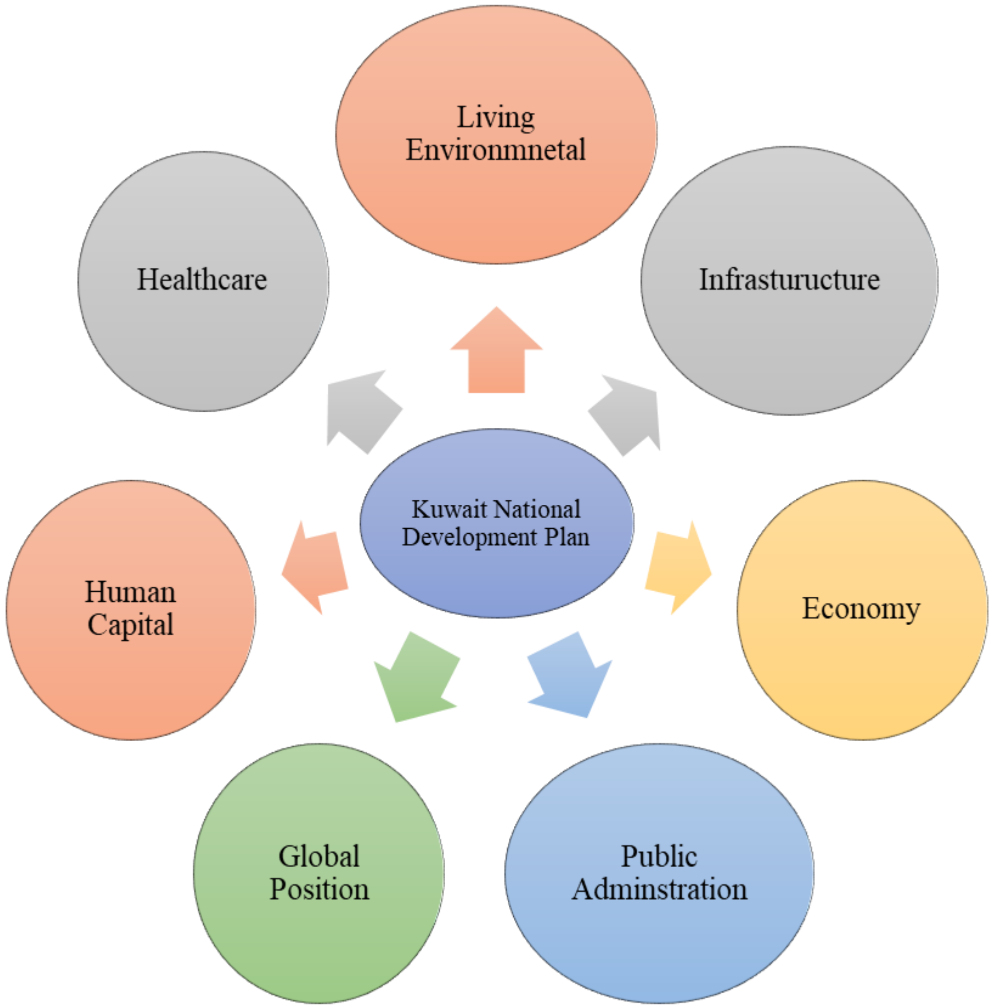


Figure 49. Kuwait National Development Plan pillars adapted from (KEPA, 2019b)

Kuwait Oil Company (KOC) plans to produce four million barrels per day by 2030, of which 50% is expected to be acquired from EOR techniques (Alajmi, et al., 2015). Three major projects have been put in place to develop EOR techniques (Oskui, et al., 2009) (Figure 50). The State Authorities have selected miscible gas injection as a promising technique for enhanced oil production in Kuwait. Typical injectants are flue gases, a mixture of enriched gases, N_2, methane (CH_4), and CO_2 (Shokrollahi, et al., 2013).

Under certain conditions, gas becomes miscible with oil in reservoirs where theoretically, the capillary force will help to recover the remaining oil in the reservoir. In planning gas injection projects, a key factor known as Minimum Miscibility Pressure (MMP) should be first estimated. Miscible displacement can only occur when the pressure is higher than MMP. Globally, MMP can be estimated by experimental or computational methods. Slime tubes and rising bubble apparatuses are the most widely used experimental methods, in addition to Pressure Volume Temperature (PVT) cell and variable interfacial tension. These methods will have more reliable results compared to computational methods, but they are more expensive and time-consuming.

Three conventional computational methods that are widely used to estimate MMP can be classified into correlation, numerical (simulation) and analytical (EOS) methods (Table 24), according to KOC. Four major Kuwaiti reservoirs have been included in KOC's miscibility tests and gas injection projects. They are Maudad Reservoirs, Lower Burgan, Zubair Reservoirs and Minagish Oolite (Table 25) (Alajmi, et al., 2015).

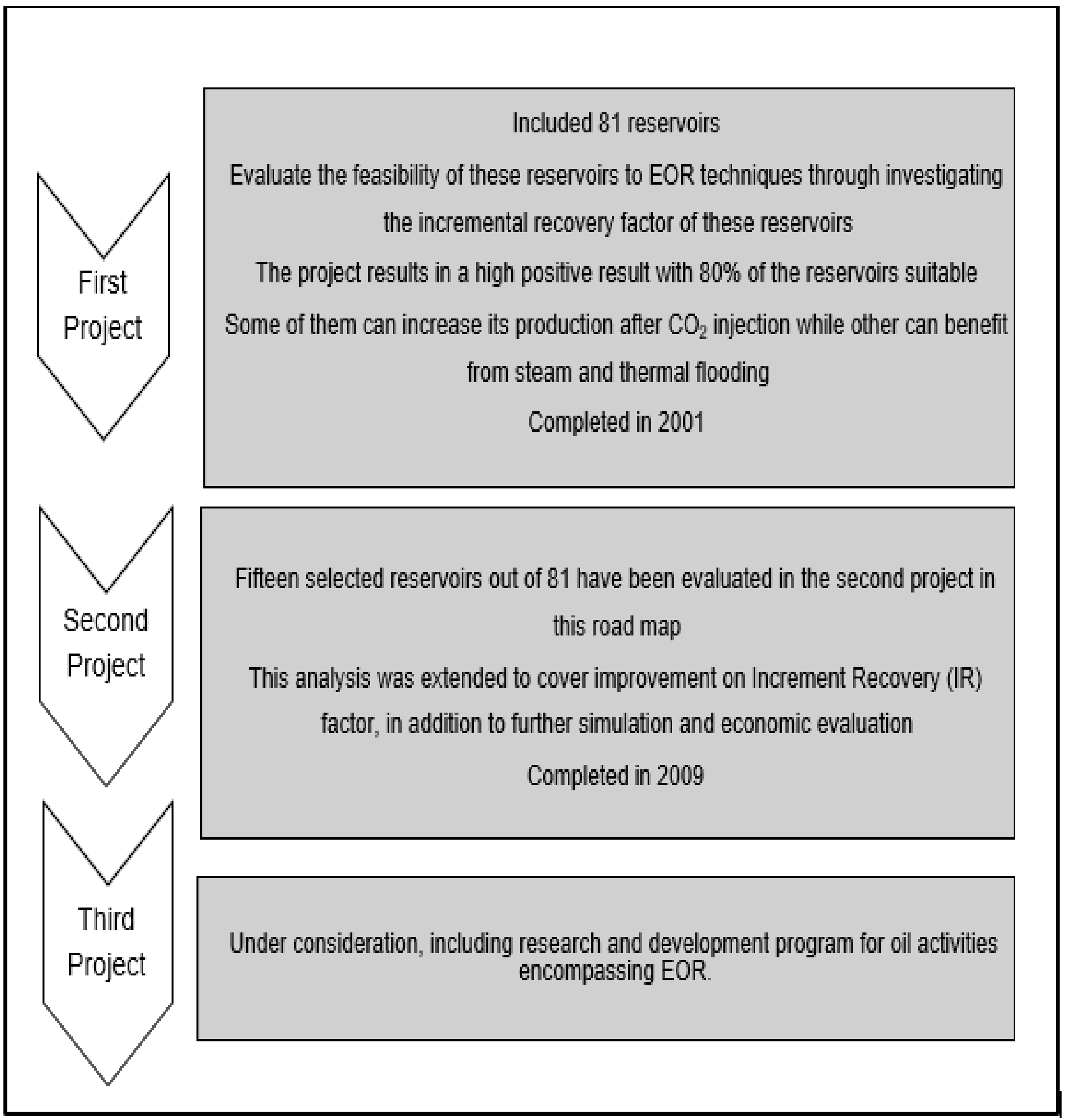


Figure 50. Kuwait government road map implementation by oil companies in developing and Improved Enhanced Oil Recovery (IOR/EOR) techniques adapted from (Oskui, et al., 2009)

Table 24. Three calculation methods used to estimate MMP

Method	Description	Example
Correlation	Is a function of different parameters where these parameters have been developed over a number of years to have more reliable results	Correlation that considers reservoir temperature and oil compositions
Numerical (simulation)	Rely on one-dimensional compositional simulation to estimate MMP in a more reliable way	Multiple mixing cell method
Analytical	Determined the miscibility behaviour by two key tie lines (initial oil and injection gas) in ternary system.	Equation of the state model, Ternary diagram, Single Mixing Cell Algorithm, Tie-line Algorithm

Source: (Alajmi, et al., 2015)

Table 25. Four Kuwaiti reservoirs that are included in the analysis

Reservoir	Maudad	Lower Burgan	Zubair	Managish
Initial year of production	1960	1950	1950	1959
MMP, psia	4500		4000	2650-3300
Test used	Slime tube analysis	EOS analysis	EOS analysis	Slime tube analysis
Current reservoir pressure, psia	3200		4585	3750- 3950
Gas used for enhancement	pure and impure CO_2	pure and impure CO_2	CO_2	CO_2

Source: (Alajmi, et al., 2015)

Crude oil, which remains in reservoirs after primary and secondary production, is known as original oil in place (OOIP). The CO_2 used in this case for the enhancement process is the gross utilization factor. It includes both new and recycled CO_2 obtained from previous injections. If CO_2 is solely injected, the gross utilization factor, up to CO_2 breakthrough, is called net utilization factor. The volume of CO_2 injected as a fraction of the hydrocarbon pore volume (HCPV) is usually used to express both the incremental oil recovery and CO_2 utilization factor. The CO_2-EOR data has been investigated globally to analyse the trend of increasing the incremental oil recovery due to the rise in HCPV after CO_2 injection. Azzolina, et al. (2015) developed the following equation to estimate the utilization factor, U_f.

$$R_f = A(1 - 1/1 + \exp\left[B \times \ln\left(\frac{x}{c}\right)\right] \tag{27}$$

$$U_f = \pi r^2 = \exp\left(D + \frac{\mathrm{E}}{\mathrm{x}}\right) \tag{28}$$

where R_f is the oil recovery factor; *x* is the total cumulative volume of injected CO_2 and water (% HCPV); *A* is the upper asymptote at infinite injection; *B* is a fitted model parameter for the slope factor of the curve between the lower and upper asymptotes; *C* is a fitted model parameter for the inflexion point where the curve changes from convex to concave; *D* is a fitted model parameter for the lower asymptote at infinite injection, and *E* is a fitted model parameter related to the slope of the curve from the maximum value (at zero % HCPV) to the lower asymptote. The formula is widely used for the study of incremental oil recovery and is applicable to Kuwait. It also presents a pathway for concerned parties, at a state level, to involve simulation in the area for a better decision-making process in this research area.

5.10 Potential CO_2 Storage in Kuwait

Saline Aquifers as Potential Sinks of CO_2: saline aquifers are reservoirs mainly composed of porous and permeable rocks saturated with saline fluid. They are usually located below a potable water table. In comparison to depleted oil and gas reservoirs, saline aquifers have a broader geographical distribution with a higher capacity of storing super-critical CO_2 (Bachu, 2003; Metz, et al., 2005; NETL, 2007; Bradshaw, et al., 2007). Both sandstone and limestone could form saline aquifer structures. Certain characteristics are required for storing CO_2 in these structures for a prolonged period of time (Bentham and Kirby, 2005). They are summarized in Figure 51.

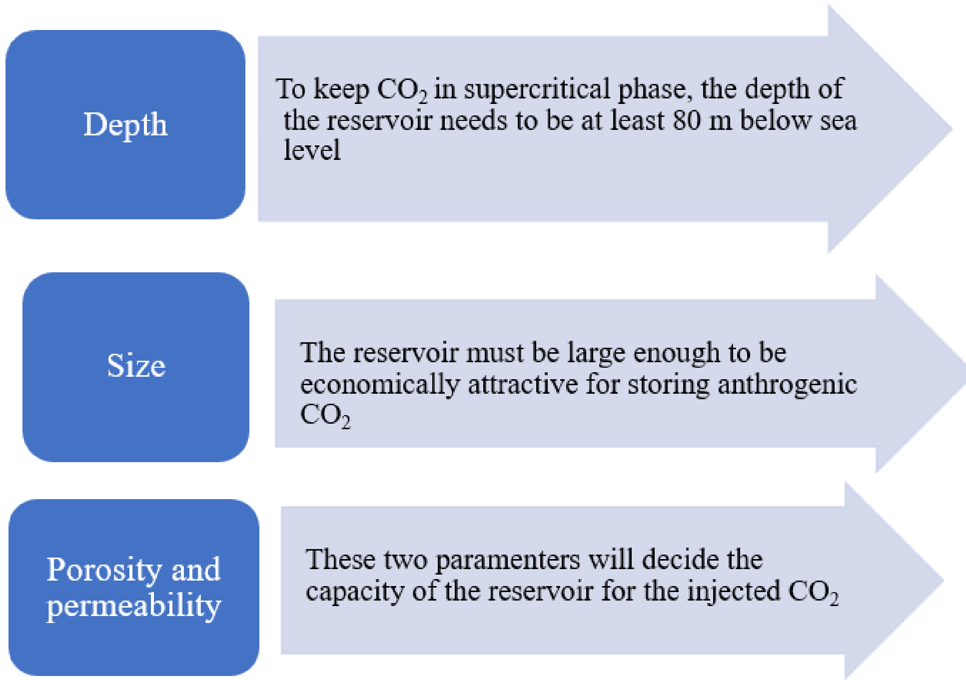


Figure 51. Characters required for long term storage of CO_2 in saline aquifer

Estimating Potential CO_2 Storage Capacity

Evaluating the CO_2 storage capacity is the first step in selecting aquifer storage. This capacity represents the total quantity of trapped CO_2 in the free, soluble, or mineral state. The theoretical CO_2 storage capacity is determined by assuming that the pore volume will be replaced by the same pore volume of CO_2. Equation 29 is used to convert pore volume m^3 into CO_2 mass (Mt):

$$m_{CO2} = V_{pore}\, P_{CO2} \qquad (29)$$

where, m_{CO_2}, V_{pore} and P_{CO2} are the mass, volume, and density of CO_2. The density of CO_2, which is assumed to be 750 kg/m^3, depends on both the temperature and pressure of the storage saline aquifer. By using this approach, KOC has estimated that the theoretical storage capacity of the entire saline aquifer in Kuwait is 7.5 Gt without taking into account any technical or economical cut-offs. The Burgan, Burgan Shallow, Ladira, and Umm Gudair are among the largest fields in terms of theoretical capacity to store CO_2 (Appendix E) (Figure 52). In this case, insufficient data and uncertainty about cap rock geological structure and reservoir thickness could affect the application of CO_2 storage in these reservoirs. Also, injecting CO_2 into deep saline aquifers presents another key technical obstacle.

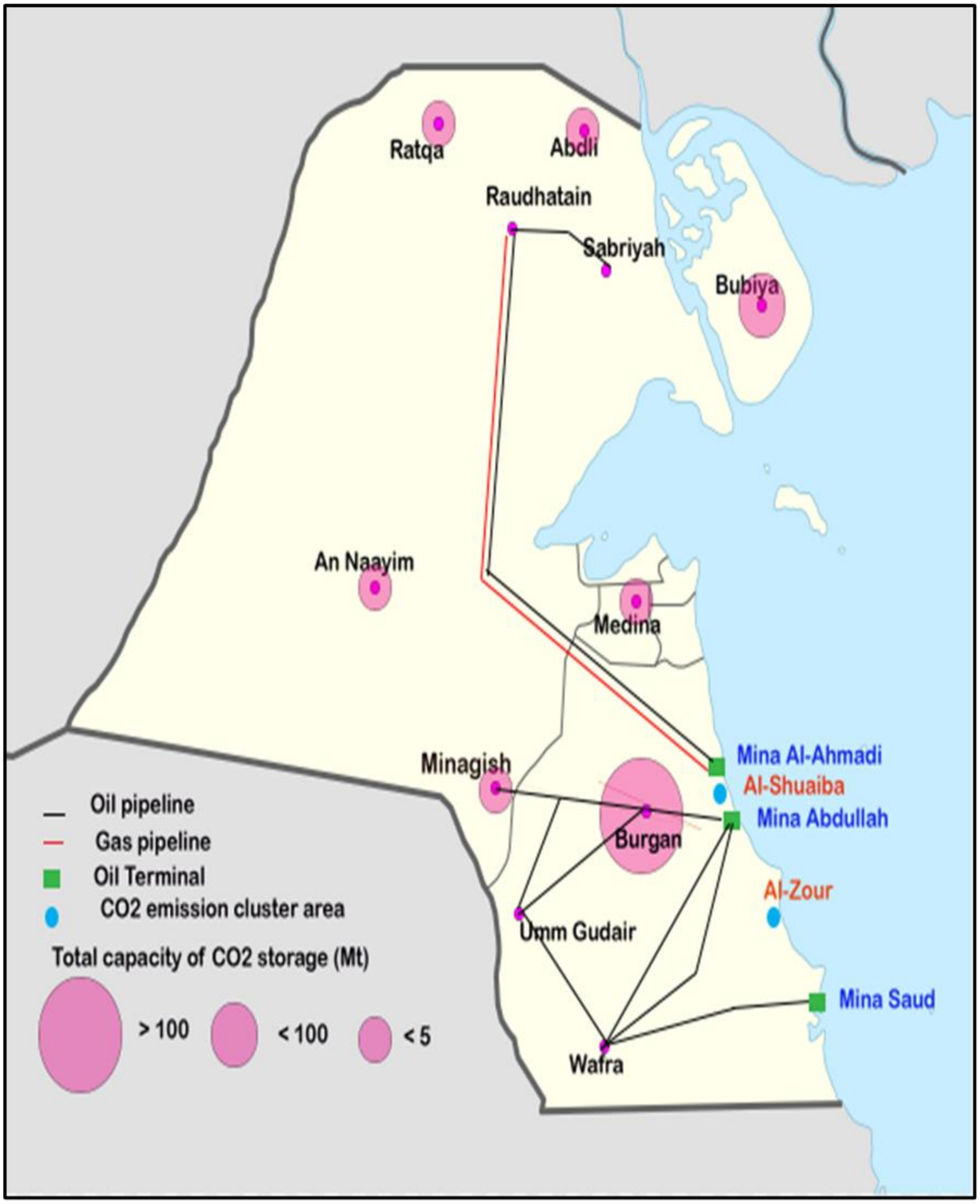


Figure 52. The potential CO_2 capacity of saline aquifer storage sites in Kuwait

In addition to these issues, there are challenges in matching the sources with the potential CO_2 storage. Distance is one of these criteria where the maximum distance, D_{max}, cannot be compromised (Bachu, 2016). The value of D_{max} varies from one place to another depending on the topographic and hydrographic features of the region. In the case of Kuwait, this distance will be much shorter in comparison to other countries, which is a notable advantage to reduce the cost of the pipeline infrastructure. Another significant criterion, *i.e.*, the storage capacity of the potential sink, must be higher than a pre-defined minimum capacity, $C_{\min}$, to make the deployment of CCUS project economically attractive (Bachu, 2016).

5.11 Manage CO_2 Injection Process

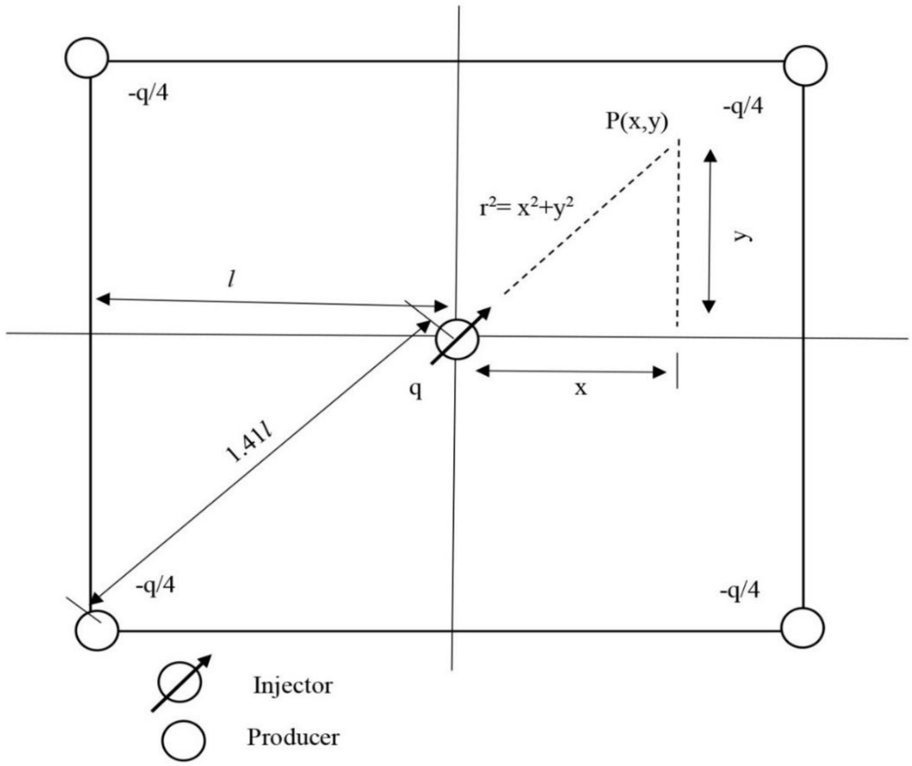
Pre-injection: during lithologies evaluation of the saline aquifer storage site, several pre-feasibility analyses were conducted first (*e.g.* screened geological data) to clarify whether there is a suitable basis for initiating the injection process. This is in addition to evaluating the porosity and permeability of the site through the drilling process to develop a pressure-repose curve, which helps in estimating the injectivity limit (Hosa, et al., 2010).

Injection Process: after the preliminary analysis of the potential area, CO_2 will be injected into deep saline formation. Injectivity of the system will determine the rate of injected CO_2 per year, where it represents the variation between the injecting rate and the excess pressure above reservoir equilibrium (Equation 30) (McCoy, 2008):

$$I=q/\left(P_{wb}-P_e\right) \tag{30}$$

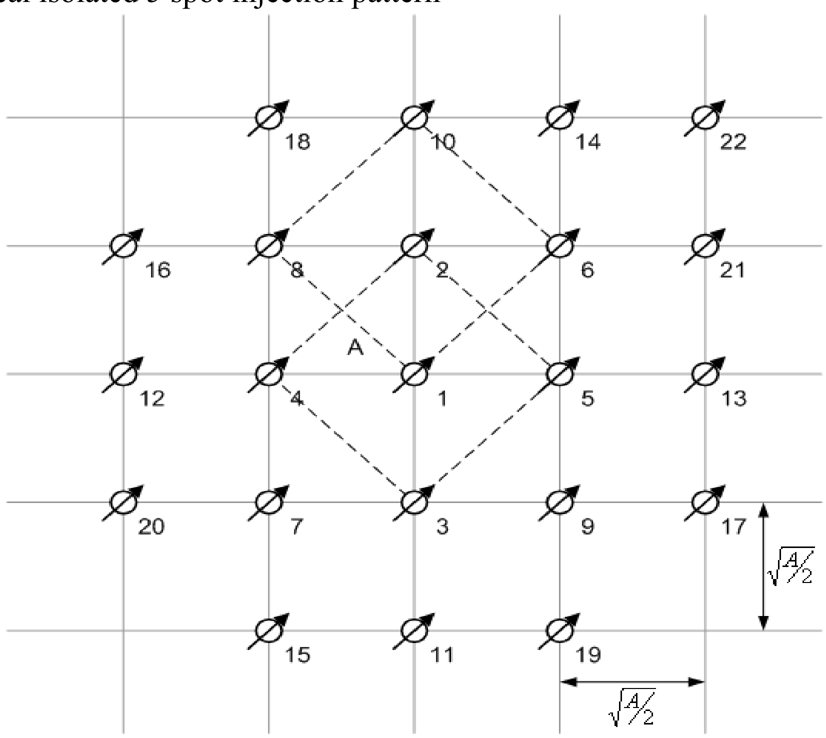
Where q is the injecting rate; P_e is the reservoir equilibrium pressure, and P_{wb} is pressure at well bottom. Figure 53 shows the typical isolated inverted 5-spot injection pattern where the injectivity could be estimated analytically. This could be done under certain circumstances where the permeability is homogeneous, the system should be at a steady-state and both the reservoir fluid and the injected fluid should be in the same physical state.

From an engineering perspective, designing multiple injecting wells (Figure 54) is more complicated than a single injecting well due to the interaction between the pressure fields. Petroleum engineers prefer the vertices of square lattice design for this purpose. The pattern spacing, in this case, will be affected by the associated area within each injection well (McCoy, 2008).



Source: (McCoy, 2008)

Figure 53. Typical isolated 5 spot injection pattern



Source: (McCoy, 2008)

Figure 54. Multiple injecting wells

5.12 Monitoring

To avoid any leakage associated with injecting CO_2 at different operational phases (pre-injection, during injection, post-injection), various monitoring techniques have been developed for this purpose. These techniques are used to measure the distribution, phases, and mass of the injected CO_2 in the saline formation, and they are classified into several groups based on the specific lithological structure of the formation (Leung, et al., 2014) (Figure 55).

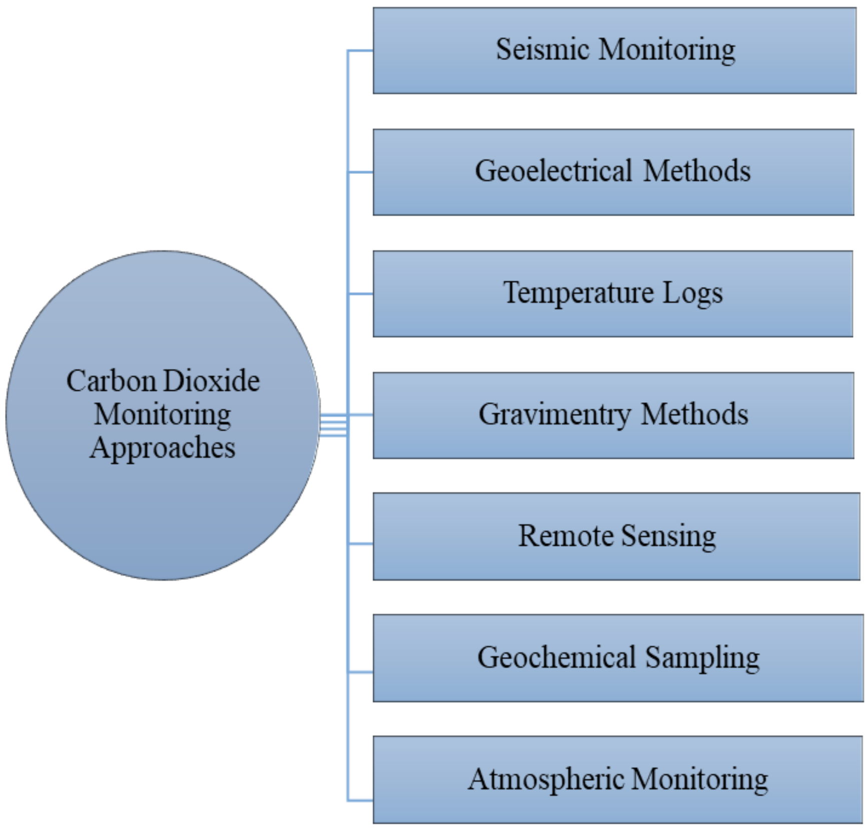


Figure 55. Carbon dioxide monitoring approaches

Seismic monitoring: seismic monitoring is used to document and compile data about the geological structure of the formation and is generally divided into active and passive systems (Ma, et al., 2013). In active systems, an energy source is used to create acoustic waves while in the passive system, geophone is employed to monitor the tremors and earthquakes yielded from the CO_2 movement through the formation (Chadwick, et al., 2008).

Geoelectrical methods: the variation in resistivity between the injected CO_2 and the displaced fluid was used in geoelectrical methods to investigate the level of CO_2 penetration inside the reservoir formation. It worth mentioning that this technique is only measures free CO_2 present in the formation (Kiessling, et al., 2010).

Temperature logs: temperature variation around the CO_2 plume can also be used to indicate the CO_2 flow path. The technique is known as temperature logs and is based on developing mathematical models such as in advective heat transfer (Liebscher, et al., 2013).

Gravimetry methods: replacing brine inside the reservoir with less dense CO_2, causes a change in underground density that can be detected by small perturbations in the local gravitational field (Smith, et al., 2012).

Remote sensing: in remote sensing, satellite monitoring is used to detect surface deformation. This deformation occurs from overpressure caused by injecting less hydraulic fluid (CO_2).

Geochemical sampling: in addition to the previous alterations in the geological formation, injecting a large volume of CO_2 could affect the chemical properties of the formation, such as the change in minerals (*e.g.* carbonates) and pH drop (Mito and Xue, 2013).

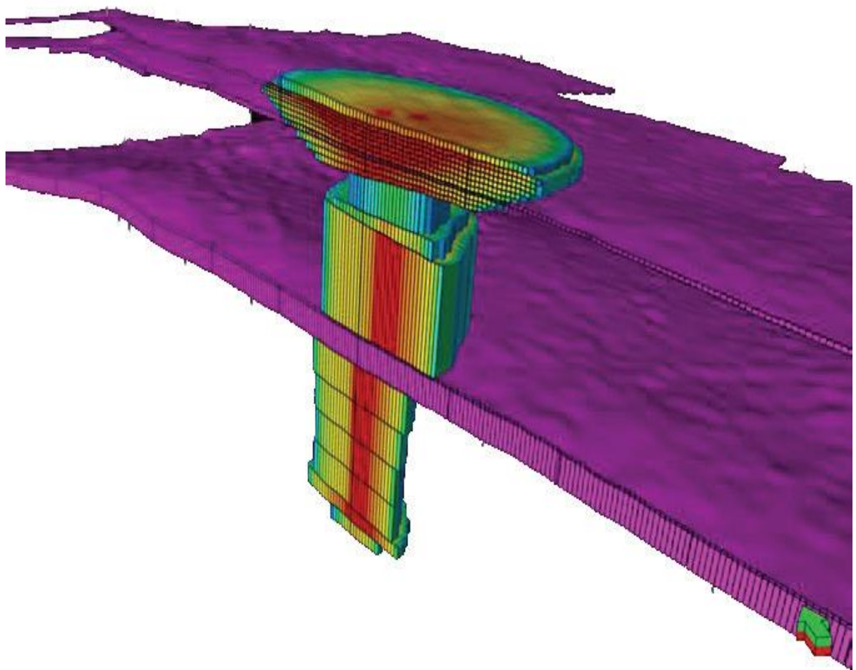
Atmospheric monitoring: in this technique, the atmospheric concentration in the target area will be monitored to identify any anomalies. The reliability of this method can be affected by natural processes such as soil respiration that increase the CO_2 concentration (Cao, et al., 2020).

5.13 Kra Al-Marh Trend: First Class CO_2 Storage Site in Kuwait

From this perspective, KOC investigated the CO_2 storage feasibility in the country through developing geological models to identify the features of all existing formations. The Jurassic formation was excluded from the analysis to avoid interference with crude oil production and due to its lower permeability. After a series of extensive evaluations and weighting of reservoirs criteria, KOC ends up with two cretaceous structures: Kra Al-Maru trend and Rahiyah structure (Neele, et al., 2017).

Kra Al-Marh extends from north to south of Kuwait in band 40 km long and 8 km wide (Neele, et al., 2017). The trend is composed of several elevations known as Kra Al-Maru subsurface anticline Umm Rijim, Khashm Al Afri, and Kahlua. The preliminary analysis shows that CO_2 plume (Figure 56) is unlikely to migrate to the neighboring Minagish oil field due to the following reasons:

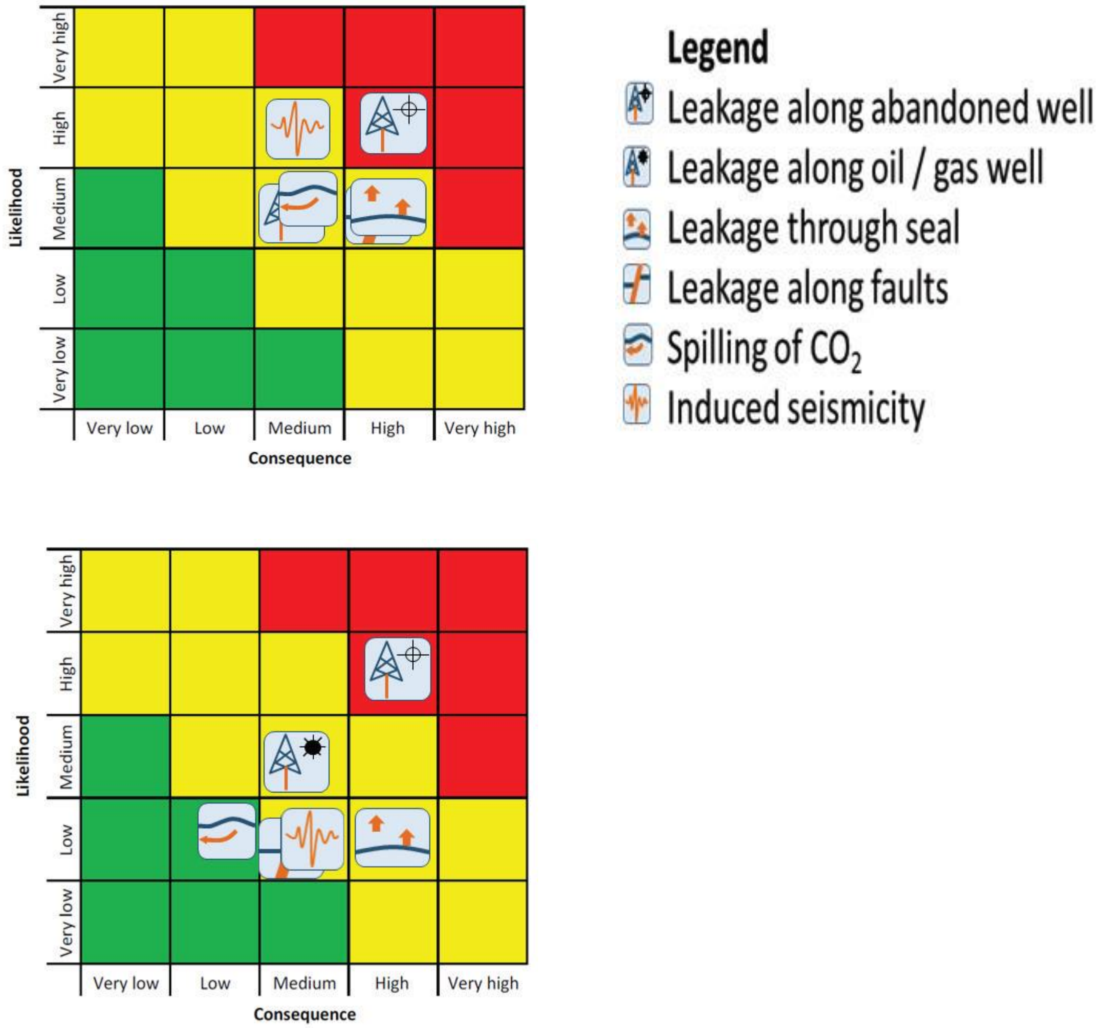
- Kra Al-Marh trend consists of three main formations: Wara, Burgan, and Zubair formations. The quality and arrangement of these formations give the trend the required feasibility for long term sequestration.
- Presence of good quality cap rock known as Ahmadi shale.
- The absence of large faults in the reservoir structure. The low number of the existing faults will help to absorb the pressure resulting from the injection process.
- Limited seismicity risks. Even at ambitious scenarios, injecting CO_2 will not lead to activation or reactivation of the existing faults.



Source: (Neele, et al., 2017)

Figure 56. 3D reservoir model of Kra Al-Marh Trends

The final risks involved in this process had been summarized in Figure 57, which considers green as low- consequence. The only high risk associated with this structure is completing the wells used for the injection and monitoring processes.



Source: (Neele, et al., 2017)

Figure 57. Initial (top) and final (bottom) risk of injecting CO_2 in Kra Al-Marh Trend

5.14 The Cost of Deploying Carbon Capture, Utilization, and Storage (CCUS)

Cost represents a major barrier to deploying CCUS technologies. The costs of avoiding and capturing CO_2 emissions are not the same, regardless of having the same unit, US dollars per tonne of CO_2. The cost of avoiding CO_2 emissions represents the quantity of CO_2 'avoided' from being emitted to the atmosphere, which usually includes the full cost of CCUS. Mathematically, it is defined as:

Cost of avoiding CO_2 emissions=$[(LCoE_{CCS}-LCoE_{Ref})/ (MOE_{Ref}- MOE_{CCS})]$ (31)

where *LCoE* is the levelized cost of electricity in USD per net MWh in a plant with and without CCUS; and *MOE* is the mass emissions rate to the atmosphere in both cases. By comparison, the cost of capturing CO_2 covers both capture and compression of CO_2 (Figure 58) to achieve the pre-defined purity values and pressure levels in meeting both pipeline and storage standards. It can be estimated mathematically as follows:

$$\text{Cost of capturing } CO_2 = ([LCoE_{CC} - LCoE_{Ref}])/MOE_{Captured} \quad (32)$$

where $LCoE_{CC}$ is the levelized cost of electricity in USD per net MWh in plant with capture, excluding the cost of CO_2 transport and storage; $MOE_{Captured}$ is the total mass of CO_2 capture per net MWh for plant capture. Compared to the cost of avoiding CO_2, capturing CO_2 presents the major cost of CCUS deployment (and therefore developing low-cost CO_2 capture technologies is the core of R&D) (Table 26).

Table 26. The role of fuel cost in effecting the capture cost

Plant	Fuel price	Reference plant COE	Capture plant COE	Capture cost
Pulverised coal combustion	USD 2.62/ GJ	87.99	141.44	74.91
Integrated coal gasification combined cycle	USD 2.62/ GJ	96.83	136.58	54,63
Natural gas combined cycle	USD 6.062/GJ	96.99	169.14	223,84

Source: (Awasthi, 2010)

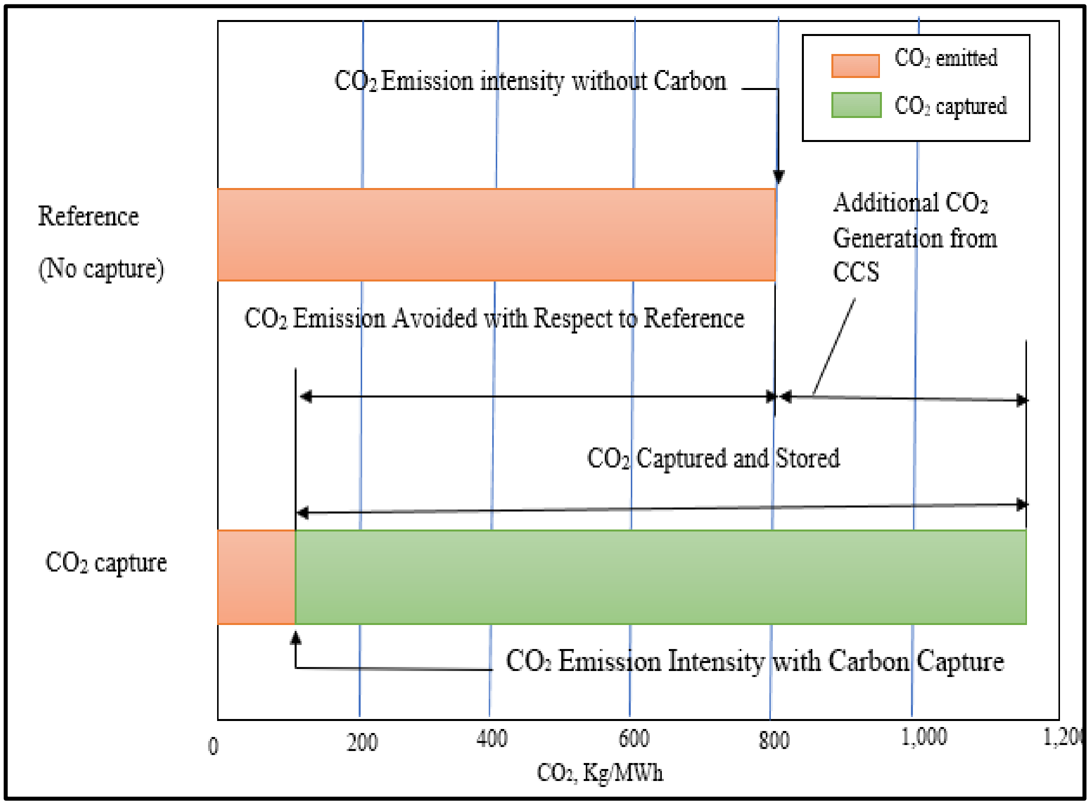


Figure 58. The total CO_2 avoided for hypothetical power generation technology adapted from (Mathieu and Bolland, 2013)

As presented in the following sub-sections, the economic burdens of deploying CCUS technologies in the industry vary significantly among individual sectors according to the operating conditions. Also, adopting different technical and economic factors in estimating the CO_2 capture costs for CCUS systems and application plants has led to a wide variation. Nevertheless, for all applications, the total cost of CO_2 capture should cover capital investment, operation, and maintenance.

Kuwait Power and Water Stations: previously, the cost of CO_2 capture was estimated based on analysis methods such as Net Present Value (NPV) (Bohm, 2006; Lindner, et al., 2009; Abadie, et al., 2003) or the Levelized Cost of Electricity (LoCE) (Porter, et al., 2017; Rubin, et al., 2015), which show discrepancies in the estimates. To overcome these discrepancies, ZEP (2011) estimated the cost of CO_2 capture, conditioning, and compression with varied fuel costs (Table 27) for the first and second generations of CO_2 capture techniques including oxy-fuel combustion, chemical looping, and absorption. The base case power plant represents the first generation of today's technological choice of CO_2 capture techniques after the demonstration phase with full economic risk. This cost is derived from the estimated cost of technologies in 2020. The optimized cost is the cost after the CCS plant has been in operation with the improvement in unit technologies, which is usually after 2025.

Table 27. Captured CO_2 costs- Gas Combined Cycle Gas Turbine

Fuel cost, USD per GJ	Base Case, USD per tonne of CO_2	Optimised cost, USD per tonne of captured CO_2
5.9	119	86
10.4	143	103
14.3	163	117

Source: (ZEP, 2011)

Refineries: the cost of deploying post-combustion or oxy-fuel combustion in refineries has been evaluated across the technical literature. Van Straelen, et al. (2010) estimated the deployment cost of post-combustion to a gasifier and a combined stack as USD 40.7 and 121.8 per t of CO_2, respectively. The estimated cost for the combined stack is significantly lower in other studies i.e., USD 68.2, 68.7, and 83.9 per t of avoided CO_2 (Farla, et al., 1995; Melien, 2005; Ho, et al., 2011). Melien (2005) reported that retrofitting the existing boilers and heaters for the oxy-fuel combustion scenario would cost around USD 65.7 per t of avoided CO_2. Due to the lack of sufficient data, a realistic cost of deploying CCUS techniques for individual sectors, including refineries, cannot be achieved at this stage. However, the cumulative cost of oxy-fuel combustion is around one-third of post-combustion, and the recent development in this technique means it will be highly competitive in the near future.

Cement, Iron, and Steel Industry: Table 28 shows the cost of deploying various carbon capture techniques in the cement industry. The post-combustion pathway will cost around USD 66.0─164.6 per t of CO_2 with a total avoided emissions for various units in a cement plant due to high thermal energy demand (Leeson, et al., 2017). The cost of oxy-fuel combustion ranges USD 17─76.9 per t of avoided CO_2. Retrofitting all units in a cement plant with full oxy-fuel combustion is technically achievable; however, the cost is only economically attractive for new cement plants. In partial oxy-fuel combustion, retrofitting preheaters and precalciners are required, and the cost is USD 67.6 per t of avoided CO_2.

Blast Furnace (BF) is the current core of research in this sector due to its intense CO_2

emissions. Arasto, et al. (2013) evaluated the deployment of post-combustion in a BF from a techno-economic perspective and concluded that the cost would range from USD 65.1–119.2 per t of CO_2. By comparison, Leeson, et al. (2017) estimated the average cost of USD 76.6 per t, with 65% of CO_2 emissions being avoided. By using the second generation of post-combustion techniques such as Selexol, the estimated cost is lower i.e., USD 17.7–19.4 per t of CO_2.

Table 28. Summary of major studies conducted on cement industry CCS costing

Author	Year	Technology	Emissions Captured (%)	Cost ($/tCO₂)
Romeo, et al (2011)	2011	Oxy combustion with calcium looping	94	17.0
Rodriguez et al (2012)	2012	Oxy combustion with calcium looping	84	23.0
IEA (2013c)	2013	Unknown on precalciner	60	35.9
Kuramochi, et al. (2012)	2012	Oxy combustion with calcium looping	60	40.6
IEA (2012b)	2012	Unknown	Unknown	49–148
IEA (2013c)	2013	Full oxy combustion	Unknown	51.4
IEA (2008a)	2008	Oxyfuel combustion	60	59.5
IEA (2013c)	2013	Unknown for whole-plant mitigation	90	61.5
Hegerland, et al (2006)	2006	Post-combustion amine scrubbing	60	66.0
IEA (2013c)	2013	Partial oxy combustion	Unknown	67.6
Barker, et al. (2009)	2009	Oxy combustion with calcium looping	52	76.9
IEA (2013c)	2013	Post-combustion on NGCC CHP	90	87.8
Kuramochi, et al. (2012)	2012	Post-combustion amine scrubbing	60	89.0
IEA (2013c)	2013	Post-combustion on coal power plant with CHP	90	148.7
Barker, et al. (2009)	2009	Post-combustion amine scrubbing	77	164.6

Transportation and Geological Storage of CO_2 Emissions: pipeline transportation is the most economical method for transporting CO_2 over a long distance. The cost of onshore construction pipes is 40 to 70% lower than that of offshore pipelines if the dimension of the pipelines remains the same. The cost will cover the construction, operation, and maintenance costs in addition to other costs (*e.g.* design and insurance fees). The cost of the CO_2 pipeline also varies significantly according to the type of terrain where the pipelines are installed. Table 29 illustrates the transported cost based on a common basis for onshore pipelines with different capacities.

Table 29. Transported costs on a common basis for onshore pipelines at three different capacities

Reference	3 Mt of CO_2/year	10 Mt of CO_2/year	30 Mt of CO_2/year
Metz, et al. (2005)	4.3- 7.2	2.2-3.7	1.3-2.2
ZEP (2011)	10.9	3.3	-
David and Time (2014)	4.9	-	1.7

The cost of CO_2 storage has been discussed in a considerable number of studies with various degrees of uncertainty. This uncertainty came from the impact of regulations on project costs in addition to public acceptance of this project. In the Metz, et al. (2005), this value ranges between USD 0.5 and 8 per t of CO_2 with an additional cost of monitoring of USD 0.1─0.3 per t of CO_2. The heterogeneity of each storage reservoir (*e.g*. reservoir type, reservoir geology) is the main cause of the variation. The appropriate CO_2 storage is characterized by onshore, shallow and high permeability rocks in addition to the potential of reusing the existing wells. Zero Emission Platform (ZEP, 2011) covered both onshore and offshore storage, in addition to differentiating between the costs in storing in saline aquifers and depleted oil and gas reservoirs. The cost of deploying a CO_2-EOR project varies with both site and localized specifications. These variations are due to the differences in geological characteristics of the target oilfield, its current state of development or depletion, and the quantity of CO_2 that will be used during the enhancement process. This cost, suggested by the Metz, et al. (2005), is USD 10─16 per t of CO_2. The drop in the oil price after 2014 has reduced the EOR credits, leading to a rise in this cost i.e. USD 15─40 per t of CO_2 (Rubin, et al., 2015).

Direct emissions from stationary sources in Kuwait are responsible for around 84% of its carbon footprint with a significant contribution in the near future. A top-down Marginal Abatement Cost (MAC) curve is usually adopted by policymakers to illustrates technical feasibility and cost-effectiveness of any climate change mitigation policy. Figure 59 depicts the

MACs for both energy and non-energy sectors in Kuwait based on previous analysis and relevant mathematical formulas (Farla, et al., 1995; Melien, 2005; Ho, et al., 2011; ZEP, 2011; Arasto, et al., 2013; Leeson, et al., 2017) (Appendix Z). All the cost figures in this analysis were converted to USD using 2018 as the base year to illustrate the impact of inflation. Figure 59 shows that CCUS has the potential to capture up to 83 Mt of CO_2 at a cost between USD 24 and 127 per t of CO_2.

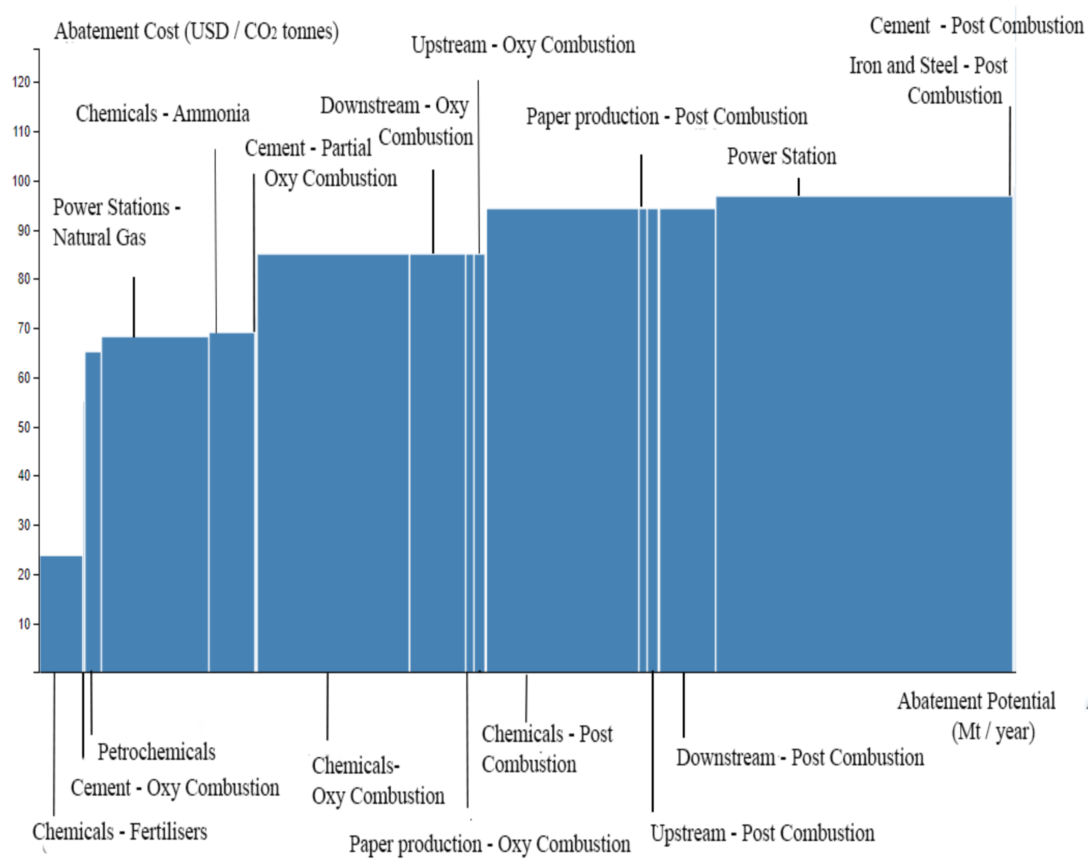


Figure 59. Abatement cost of deploying CCUS technologies in Kuwait across various industrial sectors

It is worth noting that the cost of CCUS deployment is dependent on the concentration of CO_2 emissions. Because of higher CO_2 concentration in the industrial sector, the CCUS deployment cost is less than half of that in the energy sector, except for natural gas power plants. Among all industrial sectors, high purity CO_2 streams from fertilizers, petrochemicals, and hydrogen production units present the lowest deployment cost i.e., USD 70 per t of CO_2 or below (Hendriks and Crijus-Graus, 2014; Irlam, 2017). For petrochemical and chemical industries, both post-combustion and oxyfuel combustion capture costs USD 85—94 per t of CO_2.

The cost of deploying carbon capture in natural gas power plants is lower than that of heavy oil power plants. All the upcoming power plant construction projects in Kuwait are limited to natural gas in addition to the higher number of existing natural gas power plants compared to heavy oil power plants. Both offer a potential opportunity for introducing CCUS in the power sector where the lifetime of the heavy fuel oil plants will not be long enough for the commercial stage for CCUS. With a deployment cost below USD 45 per t of CO_2, natural gas power plants will be highly competitive to the industrial sector with the advantage of "centralized-location" emissions. Figures 60-61 illustrate the cumulative cost for post-combustion and oxyfuel combustion (ZEP, 2011; Farla, et al., 1995; Melien, 2005; Ho, et al., 2011; Leeson, et al., 2017; Arasto, et al., 2013) (Appendix AA). To achieve zero emissions of CO_2, post-combustion will cost around USD 8 billion in comparison to less than USD 2.5 billion for oxy-fuel combustion. The low deployment cost, the recent development in Ionic Transport Membrane (ITM), and the short distance among the chemical factories all make oxy-fuel combustion more competitive than post-combustion in Kuwait.

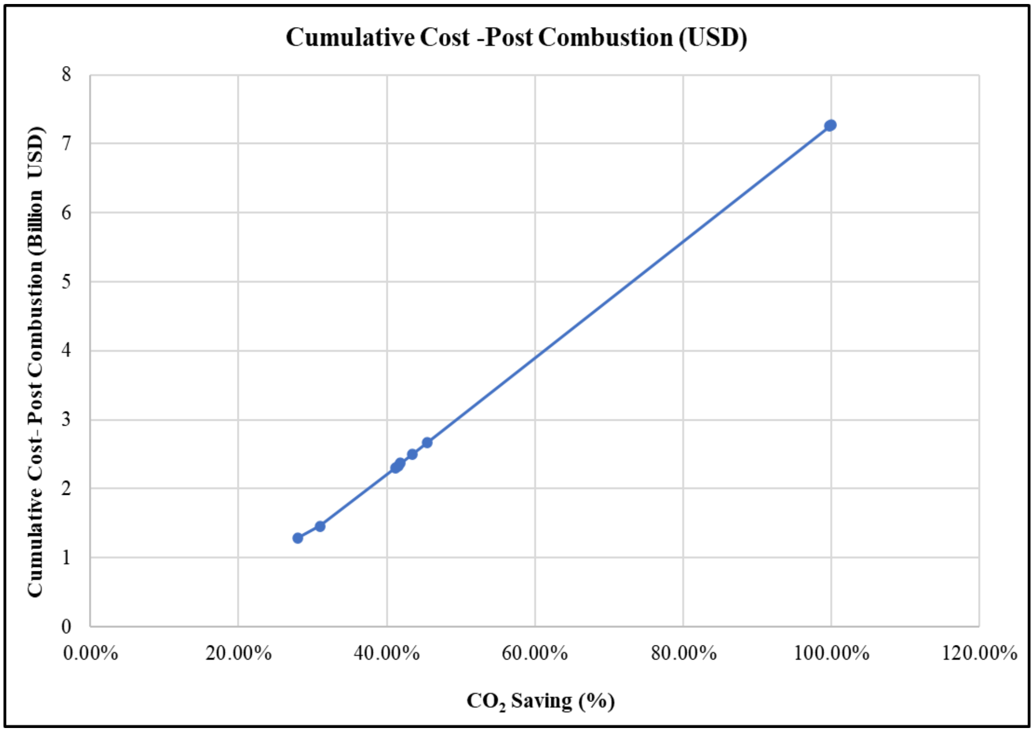


Figure 60. Cumulative cost for deploying post-combustion strategy in energy and non-energy sectors

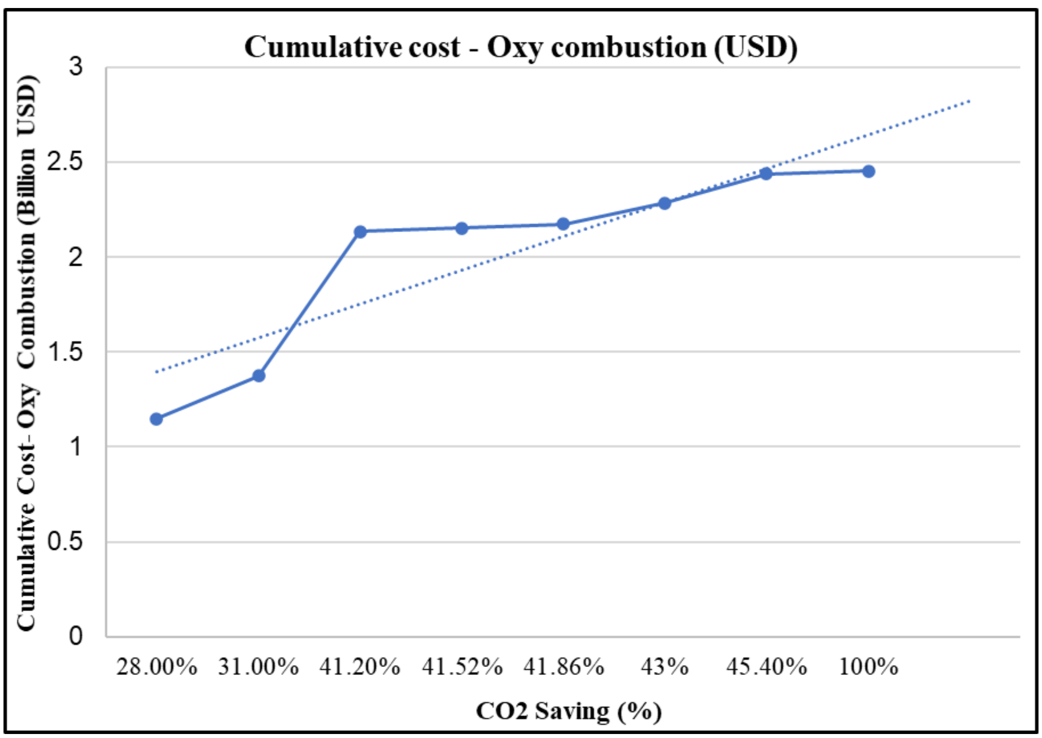


Figure 61. Cumulative cost for deploying oxy-fuel combustion strategy in energy and non-energy sectors

5.15 The risk associated with deploying carbon capture techniques

To understand the risk associated with any system, the system tree should be identified, first with its elements. In the CCUS chain, each carbon capture unit is divided into small sub-units that consist of varies elements such as heat exchangers, fans, engines, etc. After forming a good knowledge of the properties of the system elements, with particular attention to operation and technical ones, the associated hazardous scenarios were drawn. In any engineering system, these hazards could be identified as:

- Chemical hazards.
- Thermal hazards.
- Mechanical hazards.
- Electrical hazards.

The risk associated with CO_2 capture: the most mature technique of CO_2 capture is chemical absorption with amine-based solvents. The risk associated with leakage of amine could raise the fire hazard. Furthermore, it could lead to the formation of carcinogenic compounds known as nitrosamine, nitramines, and amides. The hazards of fire could also arise from uncontrolled leakage in oxygen combustion or syngas.

In addition to the risk associated with the capture process, the storage of MEA also needs to occur under certain safety conditions. Solvent degradation will rise in higher temperature conditions, which results in a loss of expensive solvents.

The risk associated with CO_2 transport: the supercritical CO_2 needs to be maintained under certain temperature and pressure during the transportation process, which raises the hazards leakage risk from transport pipes, ship tanks, and intermediate storage tanks.

The risk associated with CO_2 storage in a saline aquifer:

- *Water extraction:* saline aquifer formation in Kuwait is formed from both saline and non-saline water. In this case, CO_2 will be stored close to the potable water zone where any leakage will cause the migration of CO_2 to this zone.
- *Geothermal Energy:* one of the main renewable energies, that has an enormous potential to be fully exploited in Kuwait, is geothermal energy. This energy usually yields from a saline aquifer reservoir where the long-term storage of CO_2 will inhibit the utilization process of this energy.

- *Insufficient Data*
- *Scarcity of Saline Aquifer Data:* in contrast to the crude oil reservoir, there is a lack of sufficient data regarding saline aquifer reservoirs such as pressure measurements, seismic data, geophysical logs, etc. The demand for this data to develop the migration of CO_2 models will lead to an increase in the total cost of the injection process.
- *Characteristics of Cap Rock:* a series of testing and modeling are required to carry on illustrating the properties of caprock in eliminating any leakage of CO_2 in the future.
- *Pathway of CO_2 flow inside the aquifer*: the path of the saline aquifer is normally flowing from high to low pressure and that leads to the dissolution of CO_2. During the movement of the CO_2 to a shallower phase, it could change from super-critical to gas then escape to the surface.
- *Security Issues*: considering the security issue is highly urgent in saline aquifer reservoirs compared to depleted oil and gas fields due to less confidence in its structure where it is highly variable based on its mineralogy and petrography formations.
- Any cracks in the formation due to the decomposition of the saline rocks by CO_2/ water mixture.
- Precipitation of secondary minerals in the pore space instead of primary minerals, due to the dissolution process. Fluid pressure will rise in this case, which causes problems in the injection process.
- Cracks forms in cap rack that lead to an escape of CO_2 and failure of this cap in its function.
- Shrinkage in caprock due to the injection of dry CO_2.

Chapter 6: Policy Implementation and Recommendations

In parallel with international efforts to resolve the climate change crisis, a set of strategic contexts will need to be adopted by the Kuwait Government to fully contribute CCUS technology to the state's low carbon strategy. This roadmap has been estimated based on the experience of Western countries in this field whilst also taking into consideration the techno-economic specification of the state. (Purdy, 2006; Marston and Moore, 2008; IEA, 2010a; Klass and Wilson, 2010; Beck, et al., 2011; Russial, 2011; Crown, 2012; IEA, 2013b; Asian Development Bank, 2015). The roadmap is divided into three main phases: the next six years, known as the near-term period, between 2025-2030 (the expansion period) and after 2035, (the commercialization period) (Figure 62).

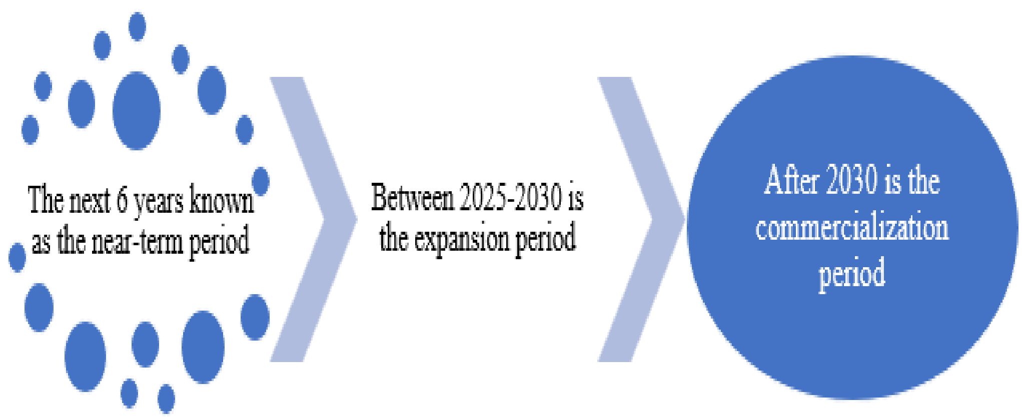


Figure 62. Roadmap for deployment of CCUS in Kuwait

6.1 Near Term Period

At this stage, CO_2 reduction will not per se, but instead create conditions for introducing CCUS strategy in the state of Kuwait through:

- Implementing CCUS regulatory framework in Low Emission Development strategy (LEDs) adopted by the Kuwait government (KEPA, 2016). It occurs after comprehensive reviews of the existing environmental regulations and extensive research undertaken in collaboration with the engagement of industry, academic, and civil society experts.
- Strengthen public and stakeholder awareness of the importance of a CCUS decarbonization strategy (Johnsson, et al., 2008; Fischedick, et al., 2009; Roberts and

Mander, 2011; Chaudhry, et al., 2013). As a new decarbonization technique in the Middle East countries, some climate and energy stakeholders may not fully understand the importance of CCUS in eliminating the significant rise in global temperature. As a result, all the relevant experts should work together to facilitate the information exchange at both the national and regional levels.

- Develop CO_2-EOR policy, after completion of the successful pilot plant in Managish reservoir (Alajmi, et al., 2015). The target of KOC is to use 20 Mt of captured CO_2 for CO_2-EOR purposes.
- Introduce financial support, from the Kuwait government, to ‘first of kind’ projects in energy and non-energy sectors. This support would be towards the high capital cost involved in this stage of pre-commercial technologies.
- Prioritize the development of a pilot plant between low-cost capture plants such as hydrogen production units in Kuwait refineries and CO_2-EOR projects.
- Introduce a CCUS ready policy for power plants under construction and study the space availability and the techno-economic barriers of retrofitting existing ones.
- Selecting the emission cluster sites represents one of the main challenges for eliminating short and long-term risks of CCUS. In this case, Al-Shuaiba and Al-Zour seem the most economically and technically suitable areas.
- Investigate the main technical and economic barriers to developing a CO_2 pipeline infrastructure.
- Gather all the data required to investigate the potential hazards associated with using the current hydrocarbon pipeline.
- Introduce regulations for CCUS in the industrial sector (Global CCS Institute, 2016; Kouri, et al., 2017; IEA, 2019). A collaboration between the government and industrial sectors will help to achieve the target cost reduction.
- Support R&D efforts into novel capture techniques that are technically feasible for GCC countries (Wilberforce, et al., 2019; Zhang, et al., 2019; Bae, et al., 2020; Yan, et al., 2020; Wang, et al., 2020). The research should mainly be focused on improving the solvents used in post and pre-combustion to achieve lower regeneration energy. Moreover, improve the reuse of excess heats present in the base plant for solvent regeneration by eliminating the corrosion problem associated with post-combustion.

6.2 Expansion Period (2025-2030)

- Smaller-scale projects (*e.g.* pilot, bench, and laboratory) will have a significant impact on developing our knowledge of the potential of CCUS (IEA, 2016). These projects are aimed at scaling up the second-generation capture technologies and the widespread adoption of these techniques across more industries.
- In the downstream petroleum sector, KNPC should construct a pilot plant in one of the current refineries to scale this strategy for the vast, intense emissions refinery that has been in operation since 2018.
- Kuwait Oil Company (KOC) should start early testing of injecting between 5,000 to 10,000 t of CO_2 in the Burgan oil field for storage purposes. This preliminary work will help the scientists to understand the behavior of CO_2 in reservoir layers and detect any migration of CO_2 outside the reservoir. At the end of the expansion stage, the later tests should increase from 30,000 t to 50,000 t.
- The EOR process in Managish reservoir will start during this stage and involve injecting one million metric tons of CO_2 with more than 95% level of impurities.
- Ministry of Electricity and Water would also need to construct the pilot projects in the electric sector through retrofitting the intense emissions power plants with the first-generation carbon capture technologies. The retrofitting process is more economically attractive than the construction of solar and wind technologies.
- At this stage, individual industrial sectors need to develop pilot-scale tests for cement kilns, steel blast furnaces, and catalytic crackers. Further research will be required in excess heat recycling for more cost-effective capture. Members of the scientific community have emphasized that CCUS techniques are the only technology that can eliminate CO_2 emissions from these high emission facilities whilst maintaining production levels.
- Ministry of General Work should start the construction process of the CO_2 pipeline infrastructure. It is not possible to reach the next stage (commercial stage) of CCUS without this type of infrastructure in place.

6.3 Commercial Period (Beyond 2030)

- The commercial system that developed in the cluster areas should enter the operational phase with more than 85% capture efficiency for all CO_2 concentrations. The cost of CCUS technologies will be driven down due to a rise of maturity in second-generation carbon capture technologies. At this level, these technologies will be more acceptable for decision makers due to a verifiable and effective level of safety.

- At this phase, the injection of CO_2 in the saline aquifer located in Burgan oilfield will rise to more than 50 Mt.

The roadmap carried out in this analysis was developed to achieve the core of decarbonization scenarios from CCUS technology, which is one of the recommended mitigation strategies for the state of Kuwait. It shapes the path for long term objectives through practical short-term actions. It builds around four elements: legal, geographical, economic, and technical. Each element should be addressed adequately, during a specific time frame, to create the necessary conditions for full-scale deployment.

As new technology in the state, the first phase of the plan is mainly focused on introducing the appropriate regulations for the different sectors associated with this technology. To make CCUS a reality, a portfolio of environmental regulations needs to be developed by the Kuwait government in the next five years, in both the energy and industrial sectors. Well-designed regulations are the primary stimulus for making CCUS a viable option and scale down the associated risks. Because of this, all relevant stakeholders should be engaged in both the development and assessment processes of the regulatory matrix and ensure that all the permits required can be achieved in the design timescale.

After forming the regulatory matrix, a dozen pilot projects are urgently required so that the matrix can be carefully evaluated. At least two demo projects should be successfully established in Kuwait power plants. The locations of these pilot plants, from north to south, will create a critical mass of CO_2 infrastructure which other emitters can utilize in the future.

The industrial sector is responsible for 40% of Kuwait's carbon footprint and this percentage is likely to grow over the coming years (Section 4.11). Most of these sectors are competitive in both local and global markets and that will be influenced by any rise in production cost. Because of this, experience gained from deploying pilot projects in the individual sectors is crucial to reduce the economic uncertainties associated with CCUS. Beyond economic consideration, pilot projects are urgently needed in order to understand the main technical challenges facing each sector. Some sectors require core modifications in the manufacturing process to retrofit with the capture technologies whilst for others the capture system can simply be added to the core process.

Uncertainty about the behavior of CO_2 inside the storage reservoir may lead to delays in achieving the commercial level of CCUS projects. As a result, the injection process should start only after an extensive evaluation of the target saline aquifers. A minimum of three years of operating capture and storage projects is required to form a base knowledge to move to the next wave of the projects (Chapman, 2012).

Chapter 7: Conclusion and Recommendations

7.1 Conclusion

Kuwait shares the concerns of the international community regarding the elimination of global CO_2 emitted to the atmosphere and seeks to move to a low carbon economy through adopting environmental protection laws. Carbon Capture, Utilization, and Storage (CCUS) is likely to become a game-changer technology in Kuwait and other GCC countries to meet their goals, in light of their heavy reliance on fossil fuel.

The analysis presented in this thesis has addressed 1) the potential to develop a realistic database of CO_2 emission sources in the state of Kuwait, and 2) the potential to deploy CCUS technology on these sources.

With respect to the first research question, power plants were responsible for 42% of CO_2 emissions due to the high energy demand for indoor cooling, the dramatic rise in population growth rate, and heavy energy subsidization by the Kuwait government. The chemical sector ranks second in this analysis with 26% because of the government's investment in the chemical industries that aims to reduce the reliance on oil exports. Finally, road transport accounted for roughly 16% of CO_2 emissions due to the vast increase in the number of vehicles during the last 50 years.

To answer the second research question, the total process emissions were determined in detail, which covered manufacturing emissions other than fuel combustion. It explains the variation between the real carbon footprint of Kuwait and both the World Bank 91.03 Mt CO_2/ y (WBR, 2006) and IEA 69.82 Mt CO_2/ y (IEA, 2010b) figures with differences of 7.7% and 40%, respectively. It highlights the importance of the work that has been undertaken particularly because a successful GHG mitigation policy is measured relative to historical GHGs emission benchmarks – which could well carry significant error and uncertainty.

Most of the high emission facilities are clustered in the Shuaiba, with 15.15 Mt/y and the Al-Zour, with 12.21 Mt/y, industrial areas located in the southeast of Kuwait. These high emission areas can be considered as Kuwait's CO_2 hotspots representing 40% of total carbon emissions in Kuwait.

In addressing the third question, two main scenarios were developed to estimate the state's carbon emissions in the case where economic diversification was achieved. By 2030, if the Kuwait government succeeds in raising the non-oil GDP contribution to 75% of the overall GDP, the overall amount of CO_2 emitted is forecasted to be 126 Mt, if not, it will be 118 Mt. Prior to this study, it was unclear what the environmental impact of these projects would be in terms of the carbon footprint of the state; this has been fully defined in this analysis.

In response to the fourth question, qualitative and quantitative surveys were conducted to explore stakeholder attitudes towards CCUS technologies. These surveys were important as they filled the research gap in assessing the techno-economic barriers of CCUS technologies in Kuwait. The majority of respondents believe that CCUS can achieve a major contribution in eliminating CO_2 emissions. However, some technical and economic concerns emerged during the interviews and completion of the questionnaire that would need to be addressed before widespread deployment took place.

There is limited flexibility for existing facilities to be retrofitted with carbon capture techniques and this represents the primary technical obstacle. In addition, there are space limitations associated with the development of a pipeline network particularly in intense industrial areas such as Al-Shuaiba.

From an economic perspective, the economic burdens of deploying CCUS technologies on individual industries will vary significantly depending on the operating conditions. However, the cumulative cost of oxy-combustion is approximately one-third of post-combustion and recent developments in this technique will make it highly competitive in the near future.

In answer to the fifth question, Kuwait has a great opportunity to utilize the capture of CO_2 for EOR purposes, especially for the northern oil fields with lower natural pressure. The CO_2-EOR provides a readily available pathway to sequester a large volume of CO_2 and the revenues of the oil production could potentially offset a major part of the capture cost. These revenues will support an early market entry of CCUS technology in the energy and industrial sectors.

In response to the final research question, the saline aquifer seems another promising option in Kuwait to store enormous amounts of CO_2. The theoretical capacity of the Kuwait saline aquifer is well understood and sufficient to sequester the current and future CO_2 emitted from the state. The lack of efficient data regarding the cap rock geological structure and uncertainty about reservoir thickness could affect the ability of these reservoirs to efficiently trap CO_2 for hundreds of years. To overcome these barriers, further geochemical analyses are needed to identify the precise characterization of the host reservoirs and predict the CO_2 behaviours inside these reservoirs at different time scales.

This scientific evaluation could help to pave the way to create a regime that supports CCUS policies in Kuwait and other MENA region countries. Clearly, further research will be required to validate the efficiency of this mitigation strategy in the region.

7.2 Recommendations for further work

7.2.1 Develop a regulatory framework for CCUS technologies

At this stage, the potential for deploying CCUS technology in the state of Kuwait will not become reality without supportive government policies. The most recent environmental protection law adopted by the Kuwait government (42/2014) covers many aspects of mitigation strategies, without considering CCUS as a mitigation strategy. However, the rapid development in Kuwait's economy creates an urgent need for the introduction of CCUS as an effective strategy and development of various scenarios for either modification of the current law or adoption of new legislation. The optimal scenario should meet two main criteria: effectiveness and feasibility. Effectiveness measures how successfully this scenario would contribute to the elimination of CO_2 emissions in the state. Feasibility describes how the scenario will be incorporated into the current environmental and economic regulations. Moreover, it should address the main regulatory gaps illustrated in Section 1.4.

7.2.2 Broaden the stakeholders covered by the study

One of the critical elements in shaping these scenarios is understanding the local stakeholder views towards CCUS and balancing their expectations and concerns. Through the preliminary interviews and questionnaires conducted in the analysis, there is a common agreement among stakeholders that CCUS could contribute to the management of the state's carbon emissions. In these interviews, each group has been assessed separately from each other to identify the techno-economic barriers of each sector. To move to the next level, more sectors should be involved in these analyses and engaged together to draw a CCUS strategy for the whole country.

7.2.3 Extend the scope to include techno-economic analyses of CCUS technologies

Although the current study covered the feasibility of CCUS in Kuwait from stakeholders and literature review perspectives, it is necessary to conduct techno-economic analyses based on more realistic data of the facilities considering site-specific factors. The analysis should not only reflect the current situation but also cover any future modifications in the core process which will accordingly affect the CO_2 emissions.

7.2.4 Carry out pilot plants for CO_2-EOR in the north of Kuwait

The 4D seismic geographical analysis undertaken by KOC provides a distinct advantage to understanding the geographical formation of the state, in the event of CO_2-EOR or long-term sequestration of CO_2. Moving from geographical analysis to laboratory experiments provides valuable data for simulation models to better understand CO_2 behavior inside the reservoir. Kuwait Oil Company (KOC) has currently only developed one pilot plant for CO_2-EOR at Managish reservoir, and the project should be extended to the other reservoirs, particularly those located in the north of Kuwait where their natural pressure is being gradually depleted.

7.2.5 A field optimization study for the saline aquifer reservoirs

Saline aquifer reservoirs that should be investigated include those with the highest theoretical capacity to store CO_2 and a relatively close distance to the production oil fields. The analyses should be extended to conduct more reservoir simulations and geochemical modelling alongside the laboratory tests to better understand the CO_2 behavior inside the reservoir.

List of references

Abadie, L., Galarraga, I. and Rübbelke, D. (2003) 'Evaluation of Two Alternative Carbon Capture and Storage Technologies: A Stochastic Model', *Environmental Modelling & Software*, 54, pp. 182–195. doi: 10.1016/j.envsoft.2014.01.002.

Abdul Quader, M., Ahmed, S., Ghazilla, R., Ahmed, S. and Dahari, M. (2016) 'Evaluation of criteria for CO_2 capture and storage in the iron and steel industry using the 2-tuple DEMATEL technique', *Journal of Cleaner Production*, 126, pp. 207–220. doi: 10.1016/j.jclepro.2015.10.056.

Abu-Zahra, M., Schneiders, L., Niederer, J., Feron, P. and Versteeg, G. (2007) 'CO_2 capture from power plants. Part I. A parametric study of the technical performance based on monoethanolamine', *International journal of greenhouse gas control*, 1, pp. 37–46. doi:10.1016/S1750-5836(06)00007-7.

Adams II, T., Hoseinzade, L. and Okeke, P. (2017) 'Comparison of CO_2 Capture Approaches for Fossil-Based Power Generation: Review and Meta-Study', *Processes*, 5(3), pp. 44. doi: 10.3390/pr5030044.

Alaimi, F. (2018) Personal comuincation. Kuwait National Petroleum Company (KNPC), manger corprate planing.

Alajmi, A., Algharaib, M., Gharbi, R., Alenezi, H., Almatar, B. and Al-Enezi, K. (2015) 'Experimental investigation of CO_2 miscible flood in West Kuwait', *Journal of Engineering Research*, 3, pp. 125–140. doi:10.7603/s40632-015-0027-2.

Al-Anzi, A. and Khattab, O. (2010) 'Solar conscious house design in Kuwait', *Kuwait Journal of Science and Engineering*, 37(2), pp. 59–72.

Al-Awadhi, J. and AlShuaibi, A. (2012) 'Potentiality of Zubair Formation for deep slurry injection in Kuwait', *Environmental Earth Sciences*, 67(5), pp. 1269–1280. doi: 10.1007/s12665-012-1570-x.

Algharaib, M. (2013) 'Potential research of carbon (iv) oxide enhanced oil recovery (CO_2 -EOR) in Middle East', *Journal of Engineering and Technology Research*, 5(4), pp. 87–103. doi: 10.5897/JETR2013.0304.

Al-Hamad, K. and Khan, A. (2008) ‘Total emissions from flaring in Kuwait oilfields’, American Journal of Environmental Sciences, 4(1), pp. 31–38. doi: 10.3844/ajessp.2008.31.38.

Al-Hasan, A., Ghoneim, A. and Abdullah, A. (2004) ‘Optimizing electrical load pattern in Kuwait using grid connected photovoltaic systems’, *Energy Conversion and Management*, 45, pp. 483–494. doi:10.1016/S0196-8904(03)00163-8.

Aljohani, T. and Alzahrani, A. (2014) ‘The Operation of the GCCIA HVDC Project and Its Potential Impacts on the Electric Power Systems of the Region’, *International Journal of Electronics and Electrical Engineering,* 2(3), pp. 207–213. doi: 10.12720/ijeee.2.3.207-213.

Al-Mamoori, A., Krishnamurthy, A., Rownaghi, A. and Rezaei, F. (2017) ‘Carbon Capture and Utilization Update’, *Energy Technology,* 5(6), pp. 834–849. doi: 10.1002/ente.201600747.

Almeida, E. and Carvalho, T. (2009) ‘The global environmental Kuznets curve and the Kyoto protocol’. Available at: http://www.ub.edu/sea2009.com/Papers/119.pdf (Accessed: 18 September 2017).

Al-Mudh'hi, S. (2012) ‘Action Plan for Implementing the Convention on Biological Diversity’s Programme of Work on Protected Areas’. Available at: https://www.cbd.int/doc/world/kw/kw-nbsap-powpa-en.pdf (Accessed: 17 March 2018).

Al-Nassar, W., Alhajraf, S., Al-Enizi, A. and Al-Awadhi, L. (2005) ‘Potential wind power generation in the State of Kuwait’, *Renewable Energy,* 30(14), pp. 2149–2161. doi: 10.1016/j.renene.2005.01.002.

Alotaibi, S. (2011) ‘Energy consumption in Kuwait: Prospects and future approaches’, *Energy Policy,* 39(2), pp. 637–643. doi: 10.1016/j.enpol.2010.10.036.

Alper, E. and Yuksel Orhan, O. (2017) ‘CO_2 utilization: Developments in conversion processes’, *Petroleum,* 3(1), pp. 109–126. doi: 10.1016/j.petlm.2016.11.003.

AlSabbagh, M., Ling Siu, Y., Barrett, J. and Abdel Gelil, I. (2013) ‘CO_2 emissions and fuel consumption of passenger vehicles in Bahrain: Current status and future scenarios’. Available at: http://www.see.leeds.ac.uk/fileadmin/Documents/research/sri/workingpapers/SRIPs-53.pdf (Accessed: 12 August 2019).

Alsahli, M. and AlHasem, A. (2016) ‘Vulnerability of Kuwait coast to sea level rise’, *Geografisk Tidsskrift - Danish Journal of Geography*, 116(1), pp. 56–70. doi: 10.1080/00167223.2015.1121403.

Al-Salem, S. (2015) ‘Carbon dioxide (CO_2) emission sources in Kuwait from the downstream industry: Critical analysis with a current and futuristic view’, *Energy*, 81, pp. 575–587. doi: 10.1016/j.energy.2014.12.075.

Al-Salem, S. (2017) Personal communication. Kuwait Institute for Scientific Research.

Alsamara, M., Mrabet, Z., Saleh, A., and Anwar, S. (2018) ‘The environmental Kuznets curve relationship: a case study of the Gulf Cooperation Council region’, *Environmental Science and Pollution Research*, 25, pp. 33183–33195. doi: 10.1007/s11356-018-3161-1.

Al-Sarawi, M., El-Baz, F. and Koch, M. (2006) ‘Geomorphologic controls on surface deposits of Kuwait as depicted in satellite images’, *Kuwait Journal of Science and Engineering*, 33(2), pp. 123–145.

Al-Sulaimi, J. and Al-Ruwaih, F. (2004) ‘Geological, structural and geochemical aspects of the main aquifer systems in Kuwait’, *Kuwait Journal of Science and Engineering*, 31(1), pp. 149–174.

Althuluth, M., Peters, C., Berrouk, A. and Kroon, M. (2013) *Separation selectivity of various gases in the ionic liquid 1-ethyl-3-methylimidazolium tris(pentafluoroethyl)trifluorophosphate*. Available at: https://research.tue.nl/en/publications/separation-selectivity-of-various-gases-in-the-ionic-liquid-1-eth-3 (Accessed: 15 October 2018).

Alyuz, U. and Alp, K. (2014) ‘Emission inventory of primary air pollutants in 2010 from industrial processes in Turkey’, *Science of the Total Environment*, 488–489, pp. 369–381. doi: 10.1016/j.scitotenv.2014.01.123.

Anchiya, A. (2009) *Aquifer management for CO_2 sequestration*. A Thesis Submitted to the Graduate of Graduate Studies of Texas A&M University in partial fulfilment of the requirements for the degree of Master of Science in Petroleum Engineering. Texas A&M University.

Anderson, S. and Newell, R. (2003) ‘Prospects for carbon capture and storage technologies’. Available at: https://www.annualreviews.org/doi/pdf/10.1146/annurev.energy.29.082703.145619 (Accessed: 27 July 2019).

Anzi, A. and Al-shammeri, B. (2016) ‘Energy Saving Opportunities Using Building Energy Simulation for a typical Mosque in Kuwait’. Available at: https://asmedigitalcollection.asme.org/ES/proceedings-abstract/ES2010/43956/383/348056 (Accessed: 25 December 2019).

Arabian gazette (2015) *Kuwait discovers four new oilfields*. Available at: https://arabiangazette.com/kuwait-discovers-four-new-oilfields-20150420/ (Accessed: 13 December 2016).

Arasto, A., Tsupari, E., Kärki, J., Sihvonen, M. and Lilja, J. (2013) ‘Costs and potential of carbon capture and storage at an integrated steel mill’, *Energy Procedia*, 37, pp. 7117–7124. doi: 10.1016/j.egypro.2013.06.648.

Arnaut, M., Vulin, D., Lamberg, G., Juki´c, L. (2021) ‘Simulation Analysis of CO_2-EOR Process and Feasibility of CO_2 Storage during EOR’. Available at: https://www.mdpi.com/1996-1073/14/4/1154/pdf (Accessed: 6 May 2021).

Asian Development Bank (2015) ‘Roadmap for Carbon Capture and Storage Demonstration and Deployment in the people's Republic of China’. Available at: https://www.adb.org/sites/default/files/publication/175347/roadmap-ccs-prc.pdf (Accessed: 11 May 2019).

Awasthi, H. (2010) *Cost of Carbon Capture and Storage*. A Thesis Submitted in Partial Fulfilment of the Requirements for the Master degree of Philosophy in Economics. Olso University.

Azar, C., Lindgren, K. and Andersson, B. (2003) ‘Global energy scenarios meeting stringent CO_2 constraints - cost effective fuel choices in the transportation sector’, *Energy Policy*, 31, pp. 961–976. doi:10.1016/S0301-4215(02)00139-8.

Azzolina, N., Nackles, D., Gorecki, C., Peck, W., Ayash, S., Melzer, S. and Chatterjee, S. (2015) ‘CO_2 storage associated with CO_2 enhanced oil recovery: a statistical analysis of historical operations', *International Journal of Greenhouse Gas Control*, 37, pp. 384–397. doi: 10.1016/j.ijggc.2015.03.037.

Bachu, S. (2003) 'Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change', *Environmental Geology*, 44, pp. 277–289. doi: 10.1007/s00254-003-0762-9.

Bachu, S. (2016) 'Identification of oil reservoirs suitable for CO_2-EOR and CO_2 storage (CCUS) using reserves databases, with application to Alberta, Canada', *International Journal of Greenhouse Gas Control*, 44, pp. 152–165. doi:10.1016/j.ijggc.2015.11.013.

Bae, J., Chung, Y., Lee, J., Seo, H. (2020)' Knowledge spillover efficiency of carbon capture, utilization, and storage technology: A comparison among countries', *Journal of Cleaner Production*, 246, pp. 119003. doi:10.1016/j.jclepro.2019.119003.

Banks, J. and Boersma, T. (2015) ' Fostering Low Carbon Energy, Next Generation Policy to Commercialize CCS in the United States'. Available at: https://www.brookings.edu/wp-content/uploads/2016/06/low_carbon_energy_ccs_banks_boersma_final.pdf (Accessed: 8 January 2018).

Barker, D., Turner, S., Napier-Moore, P., Clark, M. and Davison, J. (2009) 'CO_2 capture in the cement industry', *Energy Procedia*, 1(1), pp. 87–94. doi:10.1016/j.egypro.2009.01.014.

Beck, B., Garrett, J., Havercroft, I., Wagner, D., and Zakkour, P. (2011) 'Development and distribution of the IEA CCS Model Regulatory Framework', *Energy Procedia*, 4, pp.5933–5940. doi:10.1016/j.egypro.2011.02.595.

Bellevrat, E. and Menanteau, P. (2009) 'Introducing carbon constraint in the steel sector: ULCOS scenarios and economic modeling'. Available at: https://halshs.archives-ouvertes.fr/halshs-00430381/document (Accessed: 21 November 2017).

Benchaita, T. (2013) 'Greenhouse Gas Emissions from New Petrochemical Plants'. Available at: https://publications.iadb.org/publications/english/document/Greenhouse-Gas-Emissions-from-New-Petrochemical-Plants-Background-Information-Paper-for-the-Elaboration-of-Technical-Notes-and-Guidelines-for-IDB-Projects.pdf (Accessed: 17 May 2019).

Bentham, M. and Kirby, G. (2005) ‘CO_2 storage in saline aquifers’, *Oil & Gas Science and Technology-Revue De L Institut Francais Du Petrole*, 60(3), pp. 559–567. doi: 10.2516/ogst:2005038.

Bergsdal, H., Strømman, A. and Hertwich, E. (2004) ‘The Aluminium Industry, Environment, Technology and Production’. Available at: http://thaiminhiejc.com/upload/files/FULLTEXT01%281%29.pdf (Accessed: 16 October 2018).

Best, D. and Beck, B. (2011) ‘Status of CCS development in China’, *Energy Procedia*, 4, pp. 6141–6147. doi: 10.1016/j.egypro.2011.02.622.

Bird, D. (2009) ‘The use of questionnaires for acquiring information on public perception of natural hazards and risk mitigation – a review of current knowledge and practice’*, Natural Hazards and Earth System Sciences,* (9), pp. 1307–1325. doi: 10.5194/nhess-9-1307-2009.

Birkholzer, J., Oldenburg, C. and Zhou, Q. (2015) ‘CO_2 migration and pressure evolution in deep saline aquifers’, *International Journal of Greenhouse Gas Control*, 40, pp. 203–220. doi: 10.1016/j.ijggc.2015.03.022.

Biswas, W. (2014) ‘Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia’, *International Journal of Sustainable Built Environment*. The Gulf Organisation for Research and Development, 3(2), pp. 179–186. doi: 10.1016/j.ijsbe.2014.11.004.

Bjerge, L. and Brevik, P. (2014) ‘CO_2 capture in the cement industry, Norcem CO_2 capture project (Norway)’, *Energy Procedia*, 36, pp. 6455–6463. doi: 10.1016/j.egypro.2014.11.680.

Bohm, M. (2006) *Capture-Ready Power Plants - Options, Technologies and Economics*. Submitted to the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degree of Master of Science in Technology and Policy. Massachusetts Institute of Technology.

Bouderbala, A., Remini, B., and Hamoudi, A. (2016) ‘Geoelectrical investigation of saline water intrusion into freshwater aquifers: A case study of Nador coastal aquifer, Tipaza, Algeria’. Available at: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0016-71692016000400239&lng=es&nrm=iso (Accessed: 25 July 2018).

Bowe, K., Rainbow, T. and Boer, F. (2017) 'Glasgow Airport Carbon Footprint 2016'. Available at: https://www.glasgowairport.com/media/1713/glasgow-airport-carbon-footprint-report-2016_public_final.pdf (Accessed: 2 August 2017).

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N. and Mathiassen, O. (2007) 'CO_2 storage capacity estimation: Issues and development of standards', *International Journal of Greenhouse Gas Control*, pp. 62–68. doi:10.1016/S1750-5836(07)00027-8.

Bredeson, L., Quiceno-Gonzalez, R., Riera-Palou, X. and Harrison, A. (2010) 'Factors driving refinery CO_2 intensity, with allocation into products', *The International Journal of Life Cycle Assessment*, 15(8), pp. 817–826. doi: 10.1007/s11367-010-0204-3.

Brooking Education (2016) 'Chapter 2: Carbon Capture and Storage'. Available at: https://www.brookings.edu/wp-content/uploads/2016/07/02-low-carbon-energy-transitions-qatar-meltzer-hultman-chapter-2-1.pdf (Accessed: 16 November 2017).

Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N., Hawkes, A. (2018) 'An assessment of CCS costs, barriers and potential', *Energy Strategy Reviews*, 22, pp. 61–81. doi: 10.1016/j.esr.2018.08.003.

Cao, C., Liu, H., Hou, Z., Mehmood, F., Liao, J., Feng, W. (2020) 'A Review of CO_2 Storage in View of Safety and Cost-Effectiveness'. Available at: https://www.mdpi.com/1996-1073/13/3/600 (Accessed: 19 November 2020).

Carbon Trust (2011) *Industrial energy efficiency accelerator - guide to the paper sector.* Available at: https://www.polybags.co.uk/environmentally-friendly/industrial-energy-efficiency-accelerator-guide-to-the-paper-sector.pdf (Accessed: 8 February 2018).

Carman, G. (1996) 'Structural elements of onshore Kuwait', *GeoArabia*, 1(2), pp. 239–266.

Carpenter, A. (2012) 'CO_2 abatement in the iron and steel industry'. Available at: https://usea.org/sites/default/files/012012_CO2%20abatement%20in%20the%20iron%20and%20steel%20industry_ccc193.pdf (Accessed: 8 January 2016).

Cebrucean, D., Cebrucean, V. and Ionel, I. (2014) 'CO_2 capture and storage from fossil fuel power plants', in *Energy Procedia*. doi: 10.1016/j.egypro.2014.11.003.

Chadwick, A., Arts, R., Bernstone, C., May, F., Thibeau, S., and Zweigel, P. (2008) ‘Best Practice for the Storage of CO_2 in Saline Aquifers’. Available at: https://core.ac.uk/download/pdf/63085.pdf (Accessed: 26 June 2019).

Chapman, J. (2012) ‘The potential for reducing the costs of CCS in the UK: Interim Report of the UK Carbon Capture and Storage Cost Reduction Task Force’. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/198823/ccsa_ctrf_interim_report.pdf (Accessed: 9 May 2018).

Chaudhari, J., Tandel, K. and Patel, V. (2013) ‘Energy saving of Green Building Using Solar Photovoltaic Systems’, *International Journal of Innovative Research in Science, Engineering and Technology*, 2(5), pp. 1407–1416. ISSN: 2319-8753.

Chaudhry, R., Fischlein, M., Larson, J., Hall, D., Peterson, T., Wilson, E., Stephens, J. (2013) ‘Policy Stakeholders’ Perceptions of Carbon Capture and Storage: A Comparison of Four U.S. States ’, *Journal of Cleaner Production*, 52, pp. 21–32. doi:10.1016/j.jclepro.2013.02.002.

Chaves, G. (2011) *Simulation of CO_2 Sequestration in Deep Saline Aquifers, Gordon Creek field, Utah.* Master thesis for the Master of Science in Petroleum Engineering. New Mexico Institute of Mining and Technology.

Choi, H. and Strømman, A. (2013) *Hybrid life cycle assessment of steel production with carbon capture and storage*. Available at: https://www.semanticscholar.org/paper/Hybrid-life-cycle-assessment-of-steel-production-Choi/a6bc08a0659a1558d8c41f673b40c661b3662159 (Accessed: 15 December 2018).

Choi, H., Byeon, S. and Park, C. (2015) ‘Development of Ports Carbon Emission Estimation System’, *International Journal of u-and e-service, Science and Technology*, 8(8), pp. 235–242. doi: 10.14257/ijunesst.2015.8.8.24.

Chong, E., MA, N., and Tan, K. (2014) ‘Reducing carbon emission of ocean shipments by optimizing container size selection’. Available at: https://ink.library.smu.edu.sg/cgi/viewcontent.cgi?article=3443&context=sis_research (Accessed: 14 June 2019).

Civil Aviation (2016) *Total load of freighter arrival flights*. Available at: https://www.dgca.gov.kw/Statistics (Accessed: 6 October 2018).

Clark, V. and Herzog, H. (2014) 'Can "stranded" fossil fuel reserves drive CCS deployment? ', *Energy Procedia*, 63, pp. 7261–7271. doi: 10.1016/j.egypro.2014.11.762.

Climent Barba, F., Martínez-Denegri Sánchez, G., Seguí, B., Darabkhani, H. and Anthony, E. (2016) 'A technical evaluation, performance analysis and risk assessment of multiple novel oxy-turbine power cycles with complete CO_2 capture', *Journal of Cleaner Production*, 133, pp. 971–985. doi: 10.1016/j.jclepro.2016.05.189.

Colombia Climate Center (2016) *Mitigating emissions from aluminum*. Earth institute, Columbia University.

Cormos, C. (2016) 'Evaluation of reactive absorption and adsorption systems for post-combustion CO_2 capture applied to iron and steel industry', *Applied Thermal Engineering*, 105, pp. 56–64. doi: 10.1016/j.applthermaleng.2016.05.149.

Crown (2012) 'CCS Roadmap Supporting deployment of Carbon Capture and Storage in the UK'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48317/4899-the-ccs-roadmap.pdf (Accessed:15 December 2020).

Cui, H., Zhao, T. and Wu, R. (2018) 'An investment feasibility analysis of ccs retrofit based on a two-stage compound real options model', *Energies*, 11(7). doi: 10.3390/en11071711.

D'Alessandro, D., Smit, B. and Long, J. (2010) 'Carbon dioxide capture: Prospects for new materials', *A Journal of the German Chemical Society,* 49(35), pp. 6058–6082. doi: 10.1002/anie.201000431.

Dai, Z., Viswanathan H., Xiao, T., Middleton, R., Pan, F., Ampomah, W., Yang, C., Zhou, Y., Jia, W., Lee, S., Cather, M., Balch, R. and McPherson, B. (2017) 'CO_2 Sequestration and Enhanced Oil Recovery at Depleted Oil/Gas Reservoirs', *Energy Procedia*, 114, pp. 6957–6967. doi: 10.1016/j.egypro.2017.08.034.

Dancker, L., Daamen, Bart, W., Terwel, Emma, M., David, R., Diana, S., Sorin, A., Ioanna, B., Diana, C., Carmencita, C., Chris, J., Alexandra, D., Rebecca, F., Vassiliki, G., Chris, H., Nikolaos, K., Angelos, M., Robert, N., Oana, N., Katja, P., Irene, S., Constantin, S., Mike, S., Claudia, T., Hans, T., Sturle, T., Daniel, V., Julia, W., Fotini, Z. (2011) 'Scrutinizing the impact of CCS communication on opinion quality: Focus Group Discussions versus Information-Choice

Questionnaires: Results from experimental research in six countries', *Energy Procedia,* (4), pp. 6182 – 6187. doi:10.1016/j.egypro.2011.02.629.

Danloy, G., Berthelemot, A., Grant, M., Borlée, J., Sert, D., van der Stel, J., Jak, H., Dimastromatteo, V., Hallin, M., Eklund, N., Sundqvist, L., Skold, B., Lin, R., Feltera, A., Korthas, B., Muller, F., Feilmayr, C. (2009) ULCOS-Pilot testing of the low-CO_2 blast furnace process at the experimental BF in Luleå. Available at: https://www.cambridge.org/core/journals/metallurgical-research-and-technology/article/abs/ulcos-pilot-testing-of-the-lowco2-blast-furnace-process-at-the-experimental-bf-in-lulea/4EC3FFB15DA39663BC7AF3625FFF69BB (Accessed: 9 May 2017).

Darwish, M, Al-Najem, N. and Lior, N. (2009) 'Towards sustainable seawater desalting in the Gulf area', *Desalination*, 235(1–3), pp. 58–87. doi: 10.1016/j.desal.2008.07.005.

Darwish, M. (2005) 'Energy efficient Air conditioning: Case study for Kuwait', *Kuwait Journal of Science and Engineering*, 32(2), pp. 209–222.

Darwish, M. (2013) 'Towards Energy Conservation in Qatar', *Open Journal of Energy Efficiency*, 2(4), pp. 176–191. doi: 10.4236/ojee.2013.24023.

Darwish, M. and Al-Najem, N. (2005) 'The water problem in Kuwait', *Desalination*, 177(1–3), pp. 167–177. doi: 10.1016/j.desal.2004.07.053.

Darwish, M. and Darwish, A. (2008) 'Energy and water in Kuwait: A sustainability viewpoint, Part II', *Desalination*, 230(1–3), pp. 140–152. doi: 10.1016/j.desal.2007.10.019.

Darwish, M., Abdulrahim, H. and Binamer, A. (2008) 'On better utilization of gas turbines in Kuwait', *Energy*, 33(4), pp. 571–588. doi: 10.1016/j.energy.2007.11.014.

David, M., and Time, G. (2014) *FE/NETL CO_2 Transport Cost Model (2018): Description and User's Manual*. Available at: https://www.osti.gov/biblio/1556911-fe-netl-co2-transport-cost-model-description-user-manual (Accessed: 10 April 2018).

De Mello, L., Pimenta, R., Moure, G., Pravia, O., Gearhart, L., Milios, P. and Melien, T. (2009) 'A technical and economical evaluation of CO_2 capture from FCC units', *Energy Procedia*, 1(1), pp. 117–124. doi: 10.1016/j.egypro.2009.01.018.

Debek, R. and Dębek, R. (2017)' Novel catalysts for chemical CO_2 utilization'. Available at: https://tel.archives-ouvertes.fr/tel-01631497/document (Accessed: 18 June 2019).

Digne, R. and Gomez, A. (2014) ‘A Technical and Economical Evaluation of CO_2 Capture from Fluidized Catalytic Cracking (FCC) Flue Gas A Technical and Economical Evaluation of CO_2 Capture from Fluidized Catalytic Cracking (FCC) Flue Gas’, *Oil and Gas Science and Technology*, 69(6), pp. 1081–1089. doi: 10.2516/ogst/2013209.

Dillon, D., Panesar, R., Wall, R., Allam, R., White, V., Gibbins, J. and Haines, M. (2015) ‘Oxy-combustion processes for CO_2 capture from advanced supercritical PF and NGCC power plant’, *Greenhouse Gas Control Technologies*, 1, pp. 211–220. doi: 10.1016/B978-008044704-9/50022-7.

Director general of civil aviation (2016). Available at: https://www.dgca.gov.kw/en/civil-aviation/airport-terminals/kuwait-new-international-airport (Accessed: 3 September 2018).

Dooley, J., Dahowski, R. and Davidson, C. (2011) ‘CO_2-driven Enhanced Oil Recovery as a Stepping Stone to What?’. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-19557.pdf (Accessed: 5 April 2018).

Dormer, A., Finn, D., Ward, P. and Cullen, J. (2013) ‘Carbon footprint analysis in plastics manufacturing’, *Journal of Cleaner Production*, 51, pp. 133–141. doi: 10.1016/j.jclepro.2013.01.014.

Ecofys (2009) ‘Methodology for the free allocation of emission allowances in the EU ETS post 2012’. Available at: https://ec.europa.eu/clima/sites/default/files/ets/allowances/docs/bm_study-project_approach_and_general_issues_en.pdf (Accessed: 19 April 2019).

Economic and Social Commission for Western Asia (ESCWA) (2017) ‘Report on Carbon Capture Utilization and Storage Challenges and Opportunities for the Arab Region’. Available at: https://www.unescwa.org/sites/www.unescwa.org/files/page_attachments/technical_paper-report_ccus-received_from_css.pdf (Accessed: 20 December 2020).

Elmi, A. and Al Rifai, N. (2012) ‘Pollutant emissions from passenger cars in traffic congestion situation in the State of Kuwait: Options and challenges’, *Clean Technologies and Environmental Policy*, 14(4), pp. 619–624. doi: 10.1007/s10098-011-0421-x.

EQUATE Petrochemical Company (2011) ‘Sustainability Report’. Available at: https://www.equate.com/wp-content/uploads/2019/01/Sustainability-Report-2011-English.pdf (Accessed: 9 April 2016).

Escudero, A., Espatolero, S., Romeo, L., Lara, Y., Paufique, C., Lesort, A., and Liszka, M. (2016) ‘Minimization of CO_2 capture energy penalty in second generation oxy-fuel power plants’, *Applied Thermal Engineering*, 103, pp. 274–281. doi: 10.1016/j.applthermaleng.2016.04.116.

European Aluminium Association (2013) ‘Environmental Profile Report for the European Aluminium Industry’. Available at: https://european-aluminium.eu/media/1329/environmental-profile-report-for-the-european-aluminium-industry.pdf (Accessed: 3 April 2018).

European Commission (2013) ‘Energy efficiency and CO_2 emissions reduction in the steel industry Energy Consumption in the Iron and Steel Industry’. Available at: https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Energy_Efficiency_and_CO2_Reduction_in_the_Iron_and_Steel_Industry.pdf (Accessed: 5 November 2017).

Fang, Y., Bai, B., Tang, D., Shari, D. and David, W. (2010) ‘Characteristics of CO_2 sequestration in saline aquifers’, *Petroleum Science*, 7(1), pp. 83–92. doi: 10.1007/s12182-010-0010-3.

Farla, J., Hendriks, C. and Blok, K. (1995) ‘Carbon dioxide recovery from industrial processes’, *Climatic Change*, 29, pp. 439–461. doi:10.1007/BF01092428.

Fernández-Dacosta, C., Stojcheva, V. and Ramirez, A. (2018) ‘Closing carbon cycles: Evaluating the performance of multi-product CO_2 utilisation and storage configurations in a refinery’, *Journal of CO_2 Utilization*, 23, pp. 128–142. doi: 10.1016/j.jcou.2017.11.008.

Fieber, A. (2005) ‘Building Integration of Solar Energy - A Multifunctional Approach’. Available at: http://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/AvhandlingWEB_alt_Andreas.pdf (Accessed: 4 January 2019).

Figueroa, J., Fout, T., Plasynsk, S., Mcllvried, H. and Srivastava, R. (2008) ‘Advance in CO_2 capture technology-The U.S Department of Energy’s Carbon Sequestration Program’, *International Journal of greenhouse gas control*, 2, pp. 9–20. doi: 10.1016/S1750-5836(07)00094-1.

Fischedick, M., Pietzner, K., Supersberger, N., Esken, A., Kuckshinrichs, W., Zapp, P., Linßen, J., Schumann, D., Radgen, P., Cremer, C., Gruber, E., Schnepf, N., Roser, A., Idrissova, F. (2009) 'Stakeholder acceptance of carbon capture and storage in Germany', *Energy Procedia*, 1, pp. 4783 –4787. doi:10.1016/j.egypro.2009.02.304.

Flett, M., Gurton, R. and Weir, G. (2007) 'Heterogeneous saline formations for carbon dioxide disposal: Impact of varying heterogeneity on containment and trapping', *Journal of Petroleum Science and Engineering*, 57(1–2), pp. 106–118. doi: 10.1016/j.petrol.2006.08.016.

Folger, P. (2018) 'Carbon Capture and Sequestration (CCS) in the United States'. Available at: https://fas.org/sgp/crs/misc/R44902.pdf (Accessed: 8 May 2018).

Francke, I. and Castro, J. (2013) 'Carbon and water footprint analysis of a soap bar produced in Brazil by Natura Cosmetics', *Water Resources and Industry*, 1–2, pp. 37–48. doi: 10.1016/j.wri.2013.03.003.

Freeman, D. (2015) A"Bottom Up" approach to reducing U.S. Carbon emissions'. Available at: https://www.progressivepolicy.org/wp-content/uploads/2015/03/2015.03-Freeman_A-Bottom-Up-Approach-to-Reducing-US-Carbon-Emissions.pdf (Accessed: 16 December 2018).

Food and Agriculture Organization (FAO) (2014) *Kuwait: Country Profile*. Available at: http://www.fao.org/countryprofiles/index/en/?iso3=KWT(Accessed: 4 October 2019).

Galitsky, C., Chang, S., Worrell, E. and Masanet, E. (2008) 'Energy Efficiency Improvement and Cost Saving Opportunities for the Pharmaceutical Industry. Available at: https://www.energystar.gov/sites/default/files/buildings/tools/Pharmaceutical_Energy_Guide.pdf (Accessed: 23 February 2017).

Gao, T., Shen, L., Shen, M., Chen, F., Liu, L. and Gao, L. (2015) 'Analysis on differences of carbon dioxide emission from cement production and their major determinants', *Journal of Cleaner Production*, 103, pp. 160–170. doi: 10.1016/j.jclepro.2014.11.026.

Gavenas, E., Rosendahl, K. E. and Skjerpen, T. (2015) 'CO_2-emissions from Norwegian oil and gas extraction', *Energy*, 90(806). doi: 10.1016/j.energy.2015.07.025.

Geffen, C., Dooley, J. and Kim, S. (2003) 'Global Climate Change and the Transportation Sector: An Update on Issues and Mitigation Options, 9th Diesel Engine Emissions Reduction

Conference'. Available at: https://www.osti.gov/servlets/purl/828935(Accessed: 18 September 2017).

Ghanbari, S., Al-Zaabi, Y, Pickup, G., Mackay, E., Gozalpour, F., and Todd, A. (2006) Simulation of CO_2 storage in saline aquifers', *Chemical Engineering Research and Design*, 84(9 A), pp. 764–775. doi: 10.1205/cherd06007.

Gibson, A. (2011) *Reducing the Embodied Carbon Content of Asphalt*. Master thesis for the Master of Science in Renewable Energy Systems and the Environment. Strathclyde University.

Gielen, D. (2003) 'CO_2 removal in the iron and steel industry', *Energy Conversion and Management*, 44(7), pp. 1027–1037. doi: 10.1016/S0196-8904(02)00111-5.

Gillespie, I. (2012) *Quantifying the energy used in an asphalt coating plant*. Master thesis for the Master of Science. Strathclude University.

Gingerich, D. and Mauter, M. (2015) 'Quantity, Quality, and Availability of Waste Heat from United States Thermal Power Generation', *Environmental Science & Technology*, 49(14), pp. 8297–8306. doi: 10.1021/es5060989.

Giuffre', O. and Grana, A. (2011) 'Managing Greenhouse Gas Emissions for Airport Inventories: An Overview', *Journal of Sustainable Development*, 4(5), pp. 67–81. doi: 10.5539/jsd.v4n5p67.

Global Business Report (2016) ' GCC Aluminium'. Available at: https://www.gbreports.com/wp-content/uploads/2016/02/GCC-Aluminium-2016-Web-Version.pdf (Accessed: 11 May 2018).

Global CCS Institute (2011)'Economic Assessment of Carbon Capture and Storage Technologies'. Available at: https://www.globalccsinstitute.com/archive/hub/publications/12786/economic-assessment-carbon-capture-and-storage-technologies-2011-update.pdf (Accessed: 20 June 2018).

Global CCS Institute (2016) 'Global Status of CCS: Special Report, Understanding Industrial CCS Hubs and clusters'. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2019/08/Understanding-Industrial-CCS-hubs-and-clusters.pdf (Accessed: 11 May 2018).

Global CCS Institute (2017) ‘The Global Status of CCS’. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2018/12/2017-Global-Status-Report.pdf (Accessed: 20 December 2019).

Global CCS Institute (2019) ‘Carbon Neutrality: Scenarios for Deep Decarbonization’. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2019/08/Global-CCS-Institute_ARB_Comments_August_2019.pdf (Accessed: 22 July 2019).

Godec, M., Kuuskraa, V., Leeuwen, T., Melzer, L. and Wildgust, N. (2011) ‘CO_2 storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery’, *Energy Procedia,* 4, pp. 2162–2169. doi: 10.1016/j.egypro.2011.02.102.

Gothenburg Port Authority (2016) ‘Sustainable Port’. Available at: http://www.maritimecsr.com/files/reports/2016/sustainable-port-2016.pdf (Accessed: 5 January 2018).

Green, D. & Willhite, G. (1998) *Enhanced Oil Recovery*. Available at: https://store.spe.org/Enhanced-Oil-Recovery--P21.aspx (Accessed: 5 July 2018).

Griffin, C., Reed, B. and Hsu, S. (2006) ‘Comparing the embodied energy of structural systems in buildings’. Available at: http://web.pdx.edu/~cgriffin/research/cgriffin_embodied_text.pdf (Accessed: 5 December 2018).

Gu, Y. (2013) ‘Carbon Capture &Storage Policy in China’. Available at: http://columbiaclimatelaw.com/files/2016/06/Gu-2013-10-CCS-in-China.pdf (Accessed: 5 August 2017).

Gulf Capital Group Limited (2008) ‘GCC Industry Report, Manufacturing the Future’. Available at: https://www.gulfbase.com/schedulereports/gcc_industry_report090308.pdf (Accessed: 4 October 2016).

Gulf Labour Market and Migration (2013) ‘Gulf Labour Markets, Migration, and Population (GLMM) Programme’. Available at: https://gulfmigration.org/(Accessed: 27 March 2017).

Gunathilaka, L. and Gunawardana, K. (2015) ‘Carbon Footprint Calculation from Cradle to Grave: A Case Study of Rubber Manufacturing Process in Sri Lanka’, *International Journal of Business and Social Science,* 6(10), pp. 82–94.

Gundumogula, M. (2021) 'Importance of Focus Groups in Qualitative Research' Available at: https://hal.univ-lorraine.fr/hal-03126126/document (Accessed: 20 July 2021).

Gunter, B., Mitchell, B., Potter, I., Lakeman, B. and Wong, S. (2005) *The CANiCAP Program: Planning options for Technology and Knowledge Base Development for the Implementation of Carbon Capture and Transportation Research, Development and Deployment in Canada.* Available at: https://www.osti.gov/etdeweb/biblio/20715118 (Accessed: 7 September 2017).

Gupta, M. (2003) 'CO_2 Capture Technologies and Opportunities in Technology Roadmap Natural Resources Canada', pp. 18–19.

Haines, M. and Davison, J. (2009) 'Designing carbon capture power plants to assist in meeting peak power demand', *Energy Procedia*, 1(1), pp. 1457–1464. doi: 10.1016/j.egypro.2009.01.191.

Hamoda, M. (2001) 'Desalination and water resource management in Kuwait', *Desalination*, 138(1–3), pp. 385–393. doi: 10.1016/S0011-9164(01)00288-0.

Hanle, L. (2004) 'CO_2 Emissions Profile of the U.S. Cement Industry'. Available at: https://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf (Accessed: 14 April 2019).

Hao, H., Geng, Y. and Sarkis, J. (2016) 'Carbon footprint of global passenger cars: Scenarios through 2050', *Energy*, 101, pp. 121–131. doi: 10.1016/j.energy.2016.01.089.

Harrison, S., and Von Schéele, J (2009) 'Emission monitoring and reduction in aluminium production'. Available at: http://hiq.linde-gas.com/en/images/Gaseous%20Emissions%20Article_Aluminium%20International-Aug-Sep%202009_tcm899-89871.pdf (Accessed: 13 December 2017).

He, K., Huo, H., Zhang, Q., He, D., An, F., Wang, M. and Walsh, M. (2005) 'Oil consumption and CO_2 emissions in China's road transport: Current status, future trends, and policy implications', *Energy Policy*, 33(12), pp. 1499–1507. doi: 10.1016/j.enpol.2004.01.007.

Heathrow Airport Limited (2011) 'Heathrow Airport Climate Change Adaptation Reporting Power Report'. Available at: https://climate-adapt.eea.europa.eu/metadata/case-studies/assessing-adaptation-challenges-and-increasing-resilience-at-heathrow-airport/doc1_cca-report-heathrow_may2011.pdf (Accessed: 28 February 2018).

Heathrow Airport Limited (2014) *Heathrow's North-West Runway – Resource Use Assessment*. Available at: https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/about/airports-commission/technical-assessment/10_Heathrow_3RNW_-_Resource_Efficiency.pdf (Accessed: 5 November 2019).

Hegerland, G., Pande, J., Haugen, H., Eldrup, N., Tokheim, L., Hatlevik, L. (2006) 'Capture of CO_2 from a cement plant – technical possibilities and economical estimates'. Available at: https://www.researchgate.net/publication/262611768_Capture_of_CO2_from_a_cement_plant_-_technical_possibilities_and_economical_estimates (Accessed: 3 June 2017).

Hendriks, C. and Crijus-Graus, W. (2014) 'Global Carbon Dioxide Storage Potential and Costs'. Available at: https://www.researchgate.net/publication/260095614_Global_Carbon_Dioxide_Storage_Potential_and_Costs (Accessed: 8 December 2019).

Herzog, H. (1999) 'Introduction to CO_2 Separation and Capture Technologies'. Available at: https://sequestration.mit.edu/pdf/introduction_to_capture.pdf (Accessed: 3 December 2017).

Herzog, H. and Golomb, D. (2004) 'Carbon Capture and Storage from Fossil Fuel Use', *Encyclopaedia of Energy*, 1, pp. 277–287. doi: 10.1016/B0-12-176480-X/00422-8.

Herzong,H., Smekens K., Dadhich,P., Dooley,J., Fujii,Y., Hohmeyer,O. and Riahi, K. (2005) 'Carbon Dioxide Capture and Storage - IPCC Special Report'. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter8-1.pdf (Accessed: 3 August 2017).

Hills, T., Leeson, D., Florin, N. and Fennel, P. (2016) 'Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting', *Environmental Science and Technology*, 50(1), pp. 368–377. doi: 10.1021/acs.est.5b03508.

Ho, M., Allinson, G. and Wiley, D. (2011) 'Comparison of MEA capture cost for low CO_2 emissions sources in Australia', *International Journal of Greenhouse Gas Control*, 5(1), pp. 49–60. doi: 10.1016/j.ijggc.2010.06.004.

Holden, E. (2014) ‘Assessment of natura gas combined cycle plants for carbon dioxide capture and storage in gas-dominated electricity market’. Available at: www.CBI.com (Accessed: 19 December 2017).

Höök, M. and Aleklett, K. (2008) ‘A decline rate study of Norwegian oil production’, *Energy Policy*, 36(11), pp. 4262–4271. doi: 10.1016/j.enpol.2008.07.039.

Hosa, A., Esentia, M., Stewart, J. and Haszeldine, S. (2010) ‘Benchmarking worldwide CO_2 saline aquifer injections’, Available at: https://www.sccs.org.uk/images/expertise/reports/working-papers/wp-2010-03.pdf (Accessed: 15 May 2017).

Hossain, M. and Lasa, H. (2008) ‘Chemical-looping combustion (CLC) for inherent CO_2 separation- a review’, *Chemical Engineering Science*, 63, pp. 4433–4451. doi: 10.1016/j.ces.2008.05.028.

Hu, Y., Xu, G., Xu, C. and Yang, Y. (2017) ‘Thermodynamic analysis and techno-economic evaluation of an integrated natural gas combined cycle (NGCC) power plant with post-combustion CO_2 capture’, *Applied Thermal Engineering*, 111, pp. 308–316. doi: 10.1016/j.applthermaleng.2016.09.094.

Hurst, P. and Walker, G. (2005) *Post-Combustion Seperation and Capture Baseline Studies for the CCP Industrial Scenarios*. Available at: https://www.co2captureproject.org/viewresult.php?downid=158 (Accessed: 5 December 2016).

Hussan, H., Sebzali, M. and Ameer, B. (2014) ‘Efficiency improvement of steam power plants in Kuwait’, *WIT Transactions on Ecology and the Environment*, 186, pp. 173–184. doi: 10.2495/ESUS140151.

Ibrahim, M. and Atiyat, D. (2017) ‘The Impact of Building Envelope Design on Building Sustainability Using Simulation Solar Energy Software’, *Journal of Architectural Engineering Technology*, 6(2), pp. 2–7. doi: 10.4172/2168-9717.1000209.

IChemE Energy Centre (2018) ‘A Chemical Engineering Perspective on the Challenges and Opportunities of Delivering Carbon Capture and Storage at Commercial Scale. Available at: https://www.icheme.org/media/1401/ccs-report-2018.pdf (Accessed: 23 October 2018).

Intergovernmental Panel on Climate Change (IPCC)' (1997) 'Revised 1996 IPCC guidelines for national greenhouse gas inventories'. Available at: https://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html (Accessed: 16 March 2017).

Intergovernmental Panel on Climate Change (IPCC) (2006) 'Guidelines for national GHG inventories'. Available at: https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/(Accessed: 28 December 2016).

Intergovernmental Panel on Climate Change (IPCC) (2007) 'Climate change 2007: impacts, adaptation and vulnerability'. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf (Accessed: 16 May 2017).

Intergovernmental Panel on Climate Change (IPCC) (2014) 'Summary for Policymakers'. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_summary-for-policymakers.pdf (Accessed: 16 June 2018).

International Council of Chemical Association (ICCA) (2013) 'Chemical industry contributions to energy efficiency and mitigating climate change'. Available at: https://www.nikkakyo.org/sites/default/files/SummaryofTechnologyRoadmaps.pdf (Accessed: 9 December 2018).

International Energy Agency (IEA) (2000) 'CO_2 abatement in oil refineries: fired heater report'. Available at: http://content.ccrasa.com/library_1/2592%20-%20CO2%20abatement%20in%20oil%20refineries%20-%20Fired%20Heaters.pdf (Accessed: 18 December 2018).

International Energy Agency (IEA) (2007) 'CO_2 Capture Ready'. Available at: https://ieaghg.org/docs/General_Docs/Reports/2007-4%20Capture%20Ready.pdf (Accessed: 4 May 2019).

International Energy Agency (IEA) (2008a) 'CO_2 capture in the cement industry'. Available at: https://ieaghg.org/docs/General_Docs/Reports/2008-3.pdf (Accessed: 8 December 2016).

International Energy Agency (IEA) (2008b) 'CO_2 capture and storage: a key carbon abatement option'. Available at: https://iea.blob.core.windows.net/assets/7a2e4c6f-6cb3-4e40-9623-e1d61843c8ba/CCS_2008.pdf (Accessed: 26 September 2018).

International Energy Agency (IEA) (2008c) 'Combined heat and power'. Available at: https://iea.blob.core.windows.net/assets/d459f7d5-1ba7-49d9-ad56-915fba22f267/chp_report.pdf (Accessed: 7 May 2017).

International Energy Agency (IEA) (2010a) 'Carbon Capture and Storage- Model Regulatory Framework'. Available at: https://webstore.iea.org/download/direct/718 (Accessed: 26 December 2018).

International Energy Agency (IEA) (2010b) *Kuwait indicators for 2010*. Available at: https://www.iea.org/countries/kuwait (Accessed: 8 January 2017).

International Energy Agency (IEA) (2012a) 'Key world energy statistics'. Available at: https://www.oecd-ilibrary.org/energy/key-world-energy-statistics-2012_key_energ_stat-2012-en (Accessed: 19 October 2018).

International Energy Agency (IEA) (2012b) 'Energy Technology Perspectives 2012'. Available at: https://iea.blob.core.windows.net/assets/7136f3eb-4394-47fd-9106-c478283fcf7f/ETP2012_free.pdf (Accessed: 11 June 2017).

International Energy Agency (IEA) (2013a) 'Global Action to Advance Carbon Capture and Storage: A focus on Industrial Application'. Available at: https://iea.blob.core.windows.net/assets/d81a0913-cc57-4a79-ad81-7e10b8c5569b/CCS_Annex.pdf (Accessed:13 December 2019).

International Energy Agency (IEA) (2013b) 'Technology Roadmap—Carbon capture and storage'. Available at: https://www.iea.org/reports/technology-roadmap-carbon-capture-and-storage-in-industrial-applications (Accessed: 5 August 2018).

International Energy Agency (IEA) (2013c) *Deployment of CCS in the Cement Industry*. Available at: https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1016-2013-19-deployment-of-ccs-in-the-cement-industry (Accessed: 18 May 2019).

International Energy Agency (IEA) (2014) 'Energy Technology Perspectives 2014'. Available at: https://iea.blob.core.windows.net/assets/f97efce0-cb12-4caa-ab19-2328eb37a185/EnergyTechnologyPerspectives2014.pdf (Accessed: 9 December 2019).

International Energy Agency (IEA) (2016) ‘20 year of Carbon Capture and Storage—Accelerating Future deployment. Available at: https://www.oecd-ilibrary.org/deliver/9789264267800-en.pdf?itemId=/content/publication/9789264267800-en&mimeType=pdf (Accessed: 10 April 2020).

International Energy Agency (IEA) (2018) ‘Five keys to unlock CCS investment’. Available at: https://www.iea.org/reports/five-keys-to-unlock-ccs-investment (Accessed: 19 March 2019).

International Energy Agency (IEA) (2019) ‘Transforming Industry through CCUS’. Available at: https://ccsknowledge.com/pub/documents/publications/2019May_IEA_Transforming_Industry_CCUS.pdf (Accessed: 27 June 2019).

Irlam, L. (2017) ‘Global Costs of Carbon Capture and Storage 2017 Update’. Available at: https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf (Accessed: 20 September 2018).

Ishak, S. and Hashim, H. (2015) ‘Low carbon measures for cement plant - A review’, *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2014.11.003.

Izgec, O., Demiral, B., Bertin, H. and Akin, S. (2008) ‘CO_2 Injection into Saline Carbonate Aquifer Formations II: Comparison of Numerical Simulations to Experiments’, *Transport in Porous Media*, 73(1), pp. 57–74. doi: 10.1007/s11242-007-9160-1.

Jaffar, B., Oreszczyn, T. and Raslan, R. (2014) ‘A framework to evaluate the energy efficiency potential of Kuwaiti homes’, *WIT Transactions on Ecology and the Environment*, 186, pp. 25–38. doi: 10.2495/ESUS140031.

Jaju, M., Nader, F., Roure, F. and Matenco, L. (2016) ‘Optimal aquifers and reservoirs for CCS and EOR in the Kingdom of Saudi Arabia: an overview’, *Arabian Journal of Geosciences*, 9(12), pp.604. doi: 10.1007/s12517-016-2600-x.

Joana, C., Joris, M. and Evangelos, T. (2011) ‘Technical and economic characteristics of a CO_2 transmission pipeline infrastructure’. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC62502/reqno_jrc62502_aspublished.pdf (Accessed: 8 March 2017).

Johansson, M. (2014) 'Improved Energy Efficiency and Fuel Substitution in the Iron and Steel Industry'. Available at: https://www.diva-portal.org/smash/get/diva2:711353/FULLTEXT02.pdf (Accessed: 3 September 2018).

Johansson, T., Nakicenovic, N., Patwardhan, A. and Gomez-Echeverri, L. (2012) 'Global Energy Assessment Toward a Sustainable Future'. Available at: https://www.researchgate.net/publication/258260552_Global_Energy_Assessment_Toward_a_Sustainable_Future (Accessed: 9 June 2018).

Johnsson, F., Reiner, D., Itaoka, K., Herzog, H. (2008) 'Stakeholder Attitudes on Carbon Capture and Storage- an international comparison', *International Journal of Greenhouse Gas Control*, 4(2), pp. 410–418. doi:10.1016/j.ijggc.2009.09.006.

Kanchanapiya, P. (2015) 'Evaluation Of emission and reduction of greenhouse gases from upstream petrochemical industry in Thailand', *Environment Protection Engineering*, 41(2). doi: 10.5277/epe150203.

Kanniche, M., Gros-Bonnivard, R., Jaud, P., Valle-Marcos, J., Amann, J. and Bouallou, C. (2011) 'Pre-combustion, Post-combustion and Oxy-combustion in thermal power plant for CO_2 capture'. Available at: https://hal.archives-ouvertes.fr/hal-00584285/document (Accessed: 20 April 2018).

Ke, J., McNeil, M., Price, L., Khanna, N. and Zhou, N. (2013) 'Estimation of CO_2 emissions from China's cement production: Methodologies and uncertainties', 57, pp. 172–181. doi: 10.1016/j.enpol.2013.01.028.

Kiessling, D., Hattenberger, C., Schuett, H., Schilling, F., Krueger, K., Schoebel, B., Danckwardt, E., Kummerow, J. (2010) 'Geoelectrical methods for monitoring geological CO_2 storage: First results from cross-hole and surface–downhole measurements from the CO2SINK test site at Ketzin (Germany) ', *International Journal of Greenhouse Gas Control*. 4(5) , pp. 816–826. doi: 10.1016/j.ijggc.2010.05.001.

Kilpatrick, R., Goehner, A., Angen, E., McCulloch, M. and Kenyon, D. (2014) 'CCS Potential in the Oil Sands, Evaluating the Impact of Emerging Carbon Capture Technologies on Oil Sands Emissions'. Available at: https://eralberta.ca/wp-content/uploads/2017/05/2029-Pembina-CCS-Potential-in-the-Oilsands.pdf (Accessed: 20 February 2020).

Klass, A., Wilson, E.(2010) ‘Climate Change, Carbon Sequestration, and Property Rights’. Available at: https://scholarship.law.umn.edu/cgi/viewcontent.cgi?article=1175&context=faculty_articles (Accessed: 16 July 2018).

Kolmetz., K (2013) Olefin compressor, engineering design guideline’. Available at: www.klmtechgroup.com (Accessed: 8 April 2016).

Kouri, S., Tsupari, E., Kärki, J., Teir, S., Sormunen, R., Arponen, T., and Tuomaala, M. (2017) ‘The potential for CCUS in selected industrial sectors – summary of concept evaluations in Finland’, *Energy Procedia*, 114, pp.6418 –6431. doi: 10.1016/j.egypro.2017.03.1778.

Kumar, A., Noh, M., Ozah, R., Pope, G., Bryant, S., Sepehrnoori, K., and Lake, L. (2005) ‘Reservoir Simulation of CO2 Storage in Aquifers’. Available at: https://www.researchgate.net/publication/245418344_Reservoir_Simulation_of_CO2_Storage_in_Deep_Saline_Aquifers (Accessed: 15 June 2018).

Kuramochi, T. (2016) ‘Assessment of midterm CO_2 emissions reduction potential in the iron and steel industry: a case of Japan’, *Journal of Cleaner Production*, 132, pp. 81–97. doi: 10.1016/j.jclepro.2015.02.055.

Kuramochi, T., Ramírez, A., Turkenburg, W. and Faaij, A. (2012) ‘Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes’, *Progress in Energy and Combustion Science*, 38(1), pp. 87–112. doi: 10.1016/j.pecs.2011.05.001.

Kuwait and Middle East Financial Investment Company (KMEFIC) (2011) ‘Kuwait Cement Industry’. Available at: http://content.argaam.com.s3-eu-west-1.amazonaws.com/5ed6387b-9c06-47d5-b9a5-014d35e03b95.pdf (Accessed: 27 December 2016).

Kuwait Authority for Partnership Projects (2018) *Al Abdaliyah Integrated Solar Combined Cycle (ISCC)*. Available at: http://www.kapp.gov.kw/en/Al-Abdaliyah-Integrated-Solar-Combined-Cycle-(ISCC) (Accessed: 18 April 2019).

Kuwait Central statistical Bureau (CBS) (2015). Available at: http://www.csb.gov.kw/Socan_Statistic_EN.aspx?ID¼44 (Accessed: 3 February 2016).

Kuwait Environmental Public Authority (KEPA) (2016) ‘Intended Nationally Determined Contributions-The State of Kuwait’. Available at: https://epa.org.kw/Portals/0/PDF/Kuwait%20intended%20nationally%20determined%20contributions.pdf (Accessed:18 September 2017).

Kuwait Environmental Public Authority (KEPA) (2019a) ‘Air pollutants standards for the State of Kuwait’. Available at: https://epa.org.kw/ (Accessed: 24 December 2019).

Kuwait Environmental Public Authority (KEPA) (2019b) ‘First biennial update report of the state of Kuwait’. Available at: https://unfccc.int/sites/default/files/resource/State%20of%20Kuwait%20-%20BUR.pdf (Accessed: 24 August 2019).

Kuwait Foundation for the Advancement of Science (KFAS) (2017) ‘Identifying Priority Sectors in Kuwait’. Available at: https://www.kfas.org/media/f64c9492-86fc-4ca4-ac14-84838a234e82/GY_rk (Accessed: 29 February 2018).

Kuwait Mega Projects 2010-2014 (2010). Available at: http://kuwait-embassy.or.jp/pdf/kuwait-five-year-plan.pdf (Accessed: 24 November 2016).

Kuwait National Petroleum Company (KNPC) (2016) ‘Local markets’. Available at: www.knpc.com (Accessed: 29 May 2017).

Kuwait National Petroleum Company (KNPC) (2019) *Mina Al Ahmadi Refinery*. Available at: https://www.kpc.com.kw/informationcenter/pages/alahmadi-refinery.aspx (Accessed: 15 May 2019).

Kuwait National Petroleum Company (KNPC) (2020) ‘KNPC Clean Fuels Project (CFP) 2020, FEED Update Phase-Environmental Impact Statement (EIS)’. Available at: https://www.jbic.go.jp/ja/business-areas/environment/projects/pdf/46712_3.pdf (Accessed: 2 October 2020).

Kuwait Oil Company (KOC) (2008) ‘Progress and Prosperity’. Available at: https://www.kockw.com/sites/EN/Other%20Publications/Progress%20and%20Prosperity-English.pdf (Accessed : 24 July 2019).

Kuwait Steel (2016) 'Environmental policy'. Available at: http://www.kwtsteel. com/KWTSteel (Accessed: 3 April 2017).

Kvamsdal, H., Bolland, O. and Jordal, K. (2007) 'A qualitative comparison of gas turbine cycles with CO_2 capture', *Energy,* 31(1), pp. 10–24. doi: 10.1016/j.energy.2006.02.006.

Kwak, D. and Kim, J. (2017) 'Techno-economic evaluation of CO_2 enhanced oil recovery (EOR) with the optimization of CO_2 supply', *International Journal of Greenhouse Gas Control*, 58, pp. 169–184. doi: 10.1016/j.ijggc.2017.01.002.

Lassagne, O., Iliuta, M. and Goesilets, M. (2016) 'Techno-economic assessment of CO_2 capture from aluminum smelter emissions using PZ activated AMP solutions'. Available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/cjce.22437 (Accessed: 18 January 2019).

Lee, C., Lin, S. and Lewis, C. (2001) 'Devising an integrated methodology for analyzing energy use and CO_2 emissions from Taiwan's petrochemical industries', *Journal of Environmental Management*, 63(4), pp. 377–385. doi: 10.1006/jema.2001.0479.

Lee, J., Keener, T., Yang, Y. (2009) 'Potential flue gas impurities in carbon dioxide streams separated from coal-fired power plants', *Air Waste Management Association*, 59, pp. 725–732. doi: I:10.3155/1047-3289.59.6.72.

Leeson, D., Dowell, N., Shah, N., Petit, C. and Fennell, P. (2017) 'A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity source', *International Journal of Greenhouse Gas Control*, 61, pp. 71–84. doi: 10.1016/j.ijggc.2017.03.020.

Lei, Y., Zhang, Q., Nielsen, C. and He, K. (2011) 'An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990-2020', *Atmospheric Environment*, 45(1), pp. 147–154. doi: 10.1016/j.atmosenv.2010.09.034.

Leon, J., Aliaga, C., Boulougouris, G., Hortal, M., and Marti, J. (2015) 'Quantifying GHG emissions savings potential in magazine paper production: a case study on supercalendered and light-weight coated papers', *Journal of Cleaner Production*, 103, pp. 301–308. doi:10.1016/j.jclepro.2014.03.008.

Leung, D., Caramanna, G. and Maroto-valer, M. (2014) ‘An overview of current status of carbon dioxide capture and storage technologies’, *Renewable and Sustainable Energy Reviews*, 39, pp. 426–443. doi: 10.1016/j.rser.2014.07.093.

Li, H., Ditaranto, M. and Berstad, D. (2011) ‘Technologies for increasing CO_2 concentration in exhaust gas from natural gas-fired power production with post-combustion, amine-based CO_2 capture’, *Energy*, 36, pp. 1124–1133. doi: 10.1016/j.energy.2010.11.037.

Li, J., Ma, Y., McCarthy, M., Sculley, J., Yu, J., Jeong, H., Balbuena, P. and Zhou, H. (2011) ‘Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks’, *Coordination Chemistry Reviews*, 255(15–16), pp. 1791–1823. doi: 10.1016/j.ccr.2011.02.012.

Li, J., Tharakan, P., Macdonald, D. and Liang, X. (2013) ‘Technological, economic and financial prospects of carbon dioxide capture in the cement industry’, *Energy Policy*, 61, pp. 1377–1387. doi: 10.1016/j.enpol.2013.05.082.

Liang, Z., Fu, K., Idem, R., and Tontiwachwuthikul, P. (2016) ‘Review on current advances, future challenges and consideration issues for post-combustion CO_2 capture using amine-based absorbents’, *Chinese Journal of Chemical Engineering*, 24, pp.278–288. doi: 10.1016/j.cjche.2015.06.013.

Liebscher, A., Möller, F., Bannach, A., Köhler, S., Wiebach, J., Schmidt-Hattenberger, C., Weiner, M., Pretschner, C., Ebert, K., Zemke, J. (2013) ‘Injection operation and operational pressure–temperature monitoring at the CO_2 storage pilot site Ketzin, Germany-Design, results, recommendations’, *International Journal of Greenhouse Gas Control*, 15, pp. 163–173. doi: 10.1016/j.ijggc.2013.02.019.

Lindner, S., Peterson, S. and Windhorst, W. (2009) ‘An Economic and Environmental Assessment of Carbon Capture and Storage (CCS) Power Plants – A Case Study for the City of Kiel’. Available at: https://www.researchgate.net/publication/227619964_An_economic_and_environmental_assessment_of_carbon_capture_and_storage_CCS_power_plants_A_case_study_for_the_City_of_Kiel (Accessed: 18 December 2019).

Lindqvist, K., Roussanaly, S. and Anantharaman, R. (2014) ‘Multi-stage membrane processes for CO_2 capture from cement industry’, *Energy Procedia*, 63(1876), pp. 6476–6483. doi: 10.1016/j.egypro.2014.11.683.

Lindsay, I., Lowe, C., Reddy S., Bhakta, M. and Balkenende, S. (2009) ‘Designing a climate friendly hydrogen plant’, *Energy Procedia*, 1, pp. 4095–4102. doi: 10.1016/j.egypro.2009.02.217.

Li-ping, H., Ping-ping, S., Xin-wei, L., Qi-Chao, G., Cheng-sheng, W., Fangfang, L. (2015) ‘Study on CO_2 EOR and its geological sequestration potential in oil field around Yulin city’, *Journal of Petroleum Science and Engineering*, 134, pp. 199–204. doi:10.1016/j.petrol.2015.06.002.

Lowe, C., Brancaccio, N., Batten, D., Leung, C. and Waibel, D. (2011) ‘Technology assessment of hydrogen firing of process heaters’, *Energy Procedia*, 4, pp. 1058–65. doi: 10.1016/j.egypro.2011.01.155.

Lu, Y., Garner, D., Korose, C., Chen, S. and Rostam-Abadi, M. (2007) ‘Inventory of Industrial Stationary CO_2 Emissions in the Illinois Basin Sequestration Options in the Illinois Basin’. Available at: http://sequestration.org/resources/publish/MGSC_CO2_Inventory_081507.pdf (Accessed: 4 February 2017).

Lude, S., Fluri, T., Alhajraf, S., Jülch, V., Kühn, P., Marful, A. and Contreras, J. (2015) ‘Optimization of the Technology Mix for the Shagaya 2 GW Renewable Energy Park in Kuwait’, *Energy Procedia*, 69, pp. 1633–1642. doi: 10.1016/j.egypro.2015.03.120.

Luomi, M. (2014) ‘Mainstreaming Climate Policy in the Gulf Cooperation Council States’. Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/02/MEP-7.pdf (Accessed: 4 July 2017).

Ma, D. and Xue, Y. (2013) ‘Solar Energy and Residential Building Integration Technology and Application’, *International Journal of Clean Coal and Energy*, 2(2), pp. 8–12. doi: 10.4236/ijcce.2013.22B002.

Ma, J., Eason, J., Dowling, A., Biegler, L. and Miller, D. (2016) ‘Development of a first-principles hybrid boiler model for oxy-combustion power generation system’, *International Journal of Greenhouse Gas Control*, 46, pp. 136–157. doi: 10.1016/j.ijggc.2015.12.036.

Ma, J., Wang, X., Gao, R., Zhang, X., Wei, Y., Wang, Z., Ma, J., Huang, C., Liu, L., Jiang, S. and Li. L. (2013) ‘Monitoring the safety of CO_2 sequestration in jingbian field, China’, *Energy Procedia*, pp. 3469–3478. doi: 10.1016/j.egypro.2013.06.237.

Malhotra, E. (1999) ‘Portland cement industry: plant information summary’, *Portland Cement Association*, pp. 8–10.

Markaz (2015) *Alternative Energy in Fossil Fuel Rich GCC Countries*. Available at: https://www.marmoremena.com/alternative-energy-in-fossil-fuel-rich-gcc-countries/ (Accessed: 15 September 2018).

Markewitz, P. and Bongartz, R. (2018) ‘Chapter 2: Carbon Capture Technologies’, in W., Kuckshinrichs, J.-F., Hake (eds.), *Carbon Capture, Storage and Use*. pp. 13–45.

Marston, P. and Moore, P. (2008) ‘From EOR to CCS: The evolving legal and regulatory framework for carbon capture and storage’. Available at: https://www.researchgate.net/publication/265348126_From_EOR_to_CCS_The_evolving_legal_and_regulatory_framework_for_carbon_capture_and_storage (Accessed: 10 June 2019).

Martin, J., Lumbreras, J. and Rodríguez, M. (2003) ‘Testing flare emission factors for flaring in refineries’. Available at: https://www.researchgate.net/publication/237634174_TESTING_FLARE_EMISSION_FACTORS_FOR_FLARING_IN_REFINERIES (Accessed: 9 June 2018).

Martin, N., Worrell, E., Ruth, M., Price, L., Elliott, R., Shipley, A. and Thorne, J. (2000) ‘Emerging energy-efficient industrial technologies’. Available at: https://www.osti.gov/servlets/purl/840231-4Bv5Qg/native/ (Accessed: 15 March 2018).

Mathieu, P. and Bolland, O. (2013) ‘Comparison of costs for natural gas power generation with CO_2 capture’, *Energy Procedia*, 37, pp. 2406–2419. doi: 10.1016/j.egypro.2013.06.122.

McCoy, S. (2008) ‘The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs. Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Engineering & Public Policy. Carnegie Mellon University.

Medimurec, N. and Pasic, B. (2011) ‘Design and mechanical integrity of CO_2 injection wells’. Available at: https://hrcak.srce.hr/file/111497 (Accessed: 17 June 2018).

Melien, T. (2005) *Economic and cost analysis for CO_2 capture costs in the CO_2 capture project scenarios*. Available at: https://books.google.com.kw/books?hl=en&lr=&id=jdF7DAAAQBAJ&oi=fnd&pg=PA47&dq=Economic+and+cost+analysis+for+CO2+capture+costs+in+the+CO2+capture+project+scenarios&ots=WRVOpljIfC&sig=8ROUTsYRkT3jYzVFJh21o1dY524&redir_esc=y#v=onepage&q=Economic%20and%20cost%20analysis%20for%20CO2%20capture%20costs%20in%20the%20CO2%20capture%20project%20scenarios&f=false (Accessed: 7 October 2017).

Merk, O. (2014) ‘Shipping Emissions in Ports’. Available at: https://www.itf-oecd.org/sites/default/files/docs/dp201420.pdf (Accessed: 29 August 2017).

Merza, E. (2007) *Oil exports, non-oil exports and economic growth: time series analysis for Kuwait (1970-2004)*. Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Economic Science. Kansas State University.

Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L. (2005) ‘IPCC Special Report on Carbon Dioxide Capture and Storage’. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf (Accessed: 23 September 2016).

Mikulčić, H., Vujanović, M., and Duić, N. (2013) ‘Reducing the CO_2 emissions in Croatian cement industry’, *Applied Energy*, 101, pp.41–48. doi: 10.1016/j.apenergy.2012.02.083.

Mineral yearbook (2013) *Kuwait CO_2 emission from Fossil fuel, Emission from cement production*. Available at: https://knoema.com/atlas/Kuwait/topics/Environment/CO2-Emissions-from-Fossil-fuel/Emissions-fromcement-production (Accessed: 28 July 2018).

Ministry of Communication (MC), State of Kuwait (2019) ‘Marine transport Department, Directive on prevention of pollution by garbage from ships’. Available at: http://moc.gov.kw/pdf/MARPOL_1.pdf (Accessed: 15 July 2018).

Ministry of Oil (MO), State of Kuwait (2016) *Local consumption of oil*. Available at: http://www.moo.gov.kw/About-Us/Programs/Economic-Affairs/Local-Consumption-of-Energy.aspx (Accessed: 4 January 2017).

Ministry of Oil (MO), State of Kuwait (2018) ‘History of the Oil Industry in the State of Kuwait’. Available at: https://www.moo.gov.kw/about.aspx (Accessed: 5 May 2019).

Miracca, I., Crombie, M., Forsyth, J., Lowe, C., Moure, G., Iyer, M. and Bohm, M. (2013) 'The CO_2 capture project: Status and prospects of the capture program', *Energy Procedia*, 37, pp. 7825–7831. doi: 10.1016/j.egypro.2013.06.585.

Mito, S. and Xue, Z. (2013) 'Geochemical trapping of CO_2 in saline aquifer storage: Results of repeated formation fluid sampling at the Nagaoka site', *Energy Procedia*, 37, pp. 5449–5455. doi: 10.1016/j.egypro.2013.06.464.

Mohammad, R. (2008) *Geographical information system-based analysis of paleo fluvial systems in the Kuwait region*. A Thesis Submitted to the Graduate Faculty of Arts and Sciences in partial fulfilment of the requirements for the degree of Master of Science in Geology. University of Pittsburgh.

Mohammed, S., Alam, S. and Sharif, M. (2013) 'Assessment of Climate Change Scenario in the Middle-East Region'. Available at: https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/middle-east/arabian-peninsula/Alam--Sharif.--2013.--CC-Assessment-in-Middle-East.pdf (Accessed: 4 June 2018).

Mondal, M., Balsora, H., Varshney, P. (2012) 'Progress and trends in CO_2 capture/separation technologies: A review', *Energy*, 46, pp.431 –441. doi: 10.1016/j.energy.2012.08.006.

Motiei, M. (2001) 'Preparing carbon nanotubes and nested fullerenes from supercritical CO_2 by a chemical reaction', *Journal of the American Chemical Society*, 123, pp. 8624–8625.

Müller, N., Herz, G., Reichelt, E., Jahn, M. (2018) 'CO_2 Emission Reduction Potential in the Steel Industry by Integration of a Direct Reduction Process into Existing Steel Mills'. Available at: https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/107/49107596.pdf (Accessed: 3 April 2019).

NACAP (2010) 'Carbon Footprint of Pipeline Projects'. Available at: https://www.iploca.com/platform/content/element/7551/NacapPresentationCarbon-FootprintofPipelineProjects.pdf (Accessed: 5 February 2020).

Nagabhushan, D. and Thompson, J. (2019) 'Carbon Capture & Storage in The United States Power Sector'. Available at: https://www.catf.us/wp-content/uploads/2019/02/CATF_CCS_United_States_Power_Sector.pdf (Accessed: 20 December 2019).

National Council for Air and Stream Improvement Inc. (NCASI) (2005) 'Calculation Tools for Estimating Greenhouse Gas Emissions from Wood Product Facilities'. Available at: https://ghgprotocol.org/sites/default/files/Wood_Products.pdf (Accessed: 19 July 2020).

Neele, F., Vandeweijer, V., Mayyan, H., Sharma, S. and Kamal, D. (2017) 'Options for CO_2 Sequestration in Kuwait', *Energy Procedia*, 114, pp. 2827–2835. doi: 10.1016/j.egypro.2017.03.1402.

Neelis, M., Patel, M., Bach, P. and Blok, K. (2007) 'Analysis of energy use and carbon losses in the chemical industry', *Applied Energy*, 84(7–8), pp. 853–862. doi: 10.1016/j.apenergy.2007.01.015.

Nordbotten, J., Celia, M. and Bachu, S. (2005) 'Injection and storage of CO_2 in deep saline aquifers: Analytical solution for CO_2 plume evolution during injection', *Transport in Porous Media*, 58(3), pp. 339–360. doi: 10.1007/s11242-004-0670-9.

Norhasyima, R. and Mahlia, T. (2018) 'Advances in CO_2 utilization technology: A patent landscape review', *Journal of CO_2 Utilization*, 26, pp.323 –335. doi: 10.1016/j.jcou.2018.05.022.

Obafemi, A. and Kurt, S. (2016) 'Environmental impacts of adobe as a building material: The north cyprus traditional building case', *Case Studies in Construction Materials*, 4, pp. 32–41. doi: 10.1016/j.cscm.2015.12.001.

Oil and Gas Journal (2008) *Special Report: 2008 Worldwide EOR Survey.* Available at: https://www.ogj.com/drilling-production/production-operations/ior-eor/article/17218054/special-report-2008-worldwide-eor-survey (Accessed: 22 May 2017).

Olajire, A. (2010) 'CO_2 capture and separation technologies for end-of-pipe applications - A review', *Energy*, 35(6), pp. 2610–2628. doi: 10.1016/j.energy.2010.02.030.

Oreggioni, G., Brandani, S., Luberti, M. Baykan, Y., Friedrich, D. and Ahn, H. (2015) 'CO_2 capture from syngas by an adsorption process at a biomass gasification CHP plant: Its comparison with amine-based CO_2 capture', *International Journal of Greenhouse Gas Control*, 35, pp. 71–81. doi: 10.1016/j.ijggc.2015.01.008.

Organization of the Petroleum Exporting Countries (OPEC) (2015) 'Annual statistical bulletin'. Available at:

https://www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2015.pdf (Accessed: 19 September 2016).

Organization of the Petroleum Exporting Countries, (OPEC) (2016) 'Annual Statistical Bulletin'. Available at: https://www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2016.pdf (Accessed: 23 June 2017)

Oskui, G., Jumaa, M. and Abuhained, W (2009) 'Laboratory Investigation of Asphaltene Precipitation Problems During CO_2 / Hydrocarbon Injection Project for EOR Application in Kuwaiti Reservoirs'. Available at: https://www.onepetro.org/conference-paper/SPE-126267-MS (Accessed: 5 March 2017).

Pardo, N., Moya, J. and Vatopoulos, K. (2012) 'Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry'. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC74811/ld1a25543enn.pdf (Accessed: 19 June 2018).

Pigato, M., Black, S., Dussaux, D., Mao, Z., McKenna, M., Rafaty, R., and Touboul, S. (2020) 'Technology Transfer and Innovation for Low-Carbon Development'. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/33474/9781464815003.pdf?sequence=2&isAllowed=y (Accessed: 19 December 2020).

Policy Note (2016) 'Working Group on Carbon Pricing Mechanisms Interim Report presented to Federal Provincial Territorial Ministers of Finance Canadian Council of Ministers of the Environment'. Available at: https://www.policynote.ca/wp-content/uploads/2016/09/Carbon-Pricing-WG-Interim-Report-20160615.pdf (Accessed: 4 April 2017).

Porter, R., Fairweather, M., Kolster, C., Dowell, N. and Shah, N. (2017) 'Cost and performance of some carbon capture technology options for producing different quality CO_2 product streams', *International Journal of Greenhouse Gas Control*, 57, pp. 185–195. doi: 10.1016/j.ijggc.2016.11.020.

Porter, R., Fairweather, M., Pourkashanian, M. and Woolley, R. (2015) 'The range and level of impurities in CO_2 streams from different carbon capture sources', *International Journal of Greenhouse Gas Control*, 36, pp. 161–174. doi:10.1016/j.ijggc.2015.02.016.

Postorino, M. and Mantecchini, L. (2014) ‘A transport carbon footprint methodology to assess airport carbon emissions’, *Journal of Air Transport Management*, 37, pp. 76–86. doi: 10.1016/j.jairtraman.2014.03.001.

Price, L, Phylipsen, G, Worrell, E. (2001) ‘Energy use and carbon dioxide emissions in the steel sector in key developing countries’. Available at: https://www.osti.gov/biblio/783473 (Accessed: 15 May 2019).

Public Authority for Industry (PAI) (2014) ‘Industrial Guide- State of Kuwait’. Available at: www.pai.gov.kw (Accessed: 9 January 2017).

Public Intelligence (2017) ‘Kuwait Country Handbook’. Available at: https://info.publicintelligence.net/MCIA-KuwaitHandbook.pdf (Accessed: 7 October 2019).

Purdy, R. (2006) ‘The Legal Implications of Carbon Capture and Storage Under the Sea’, *Sustainable Development Law and Policy*, 7, pp. 22–26.

Quader, M., Ahmed, S., Ghazilla, R., Ahmed, S. and Dahari, M. (2016) ‘Evaluation of criteria for CO_2 capture and storage in the iron and steel industry using the 2-tuple DEMATEL technique’, *Journal of Cleaner Production*, 120, pp. 207–220. doi: 10.1016/j.jclepro.2015.10.056.

Radhi, H. and Sharples, S. (2013) ‘Global warming implications of facade parameters: A life cycle assessment of residential buildings in Bahrain’, *Environmental Impact Assessment Review*, 38, pp. 99–108. doi: 10.1016/j.eiar.2012.06.009.

Rainer, R., Miguel, A., Serge, R. and Luis, D. (2012) ‘Best Available Techniques (BAT) Reference Document:for:Iron and Steel Production’. Available at: https://ec.europa.eu/jrc/en/publication/reference-reports/best-available-techniques-bat-reference-documentforiron-and-steel-productionindustrial-emissions (Accessed: 3 March 2018).

Ramadhan, M. and Naseeb, A. (2011) ‘The cost benefit analysis of implementing photovoltaic solar system in the state of Kuwait’, *Renewable Energy*, 36(4), pp. 1272–1276. doi: 10.1016/j.renene.2010.10.004.

Raouf, M. (2008) *Climate Change Threats, Opportunities, and the GCC Countries.* The Middle East Institute-Policy Brief. Available at:

https://www.files.ethz.ch/isn/55953/No_12_Climate_Change_Threats_Opportunities_and_the_GCC_Countries.pdf (Accessed: 28 April 2017).

Ravanchi, M., and Sahebdelfar, S. (2014) 'Carbon dioxide capture and utilization in petrochemical industry: potentials and challenges', *Applied Petrochemical Research*, 4, pp.63–77. doi: 10.1007/s13203-014-0050-5.

Ray, S., Goldar, A. and Saluja, S. (2014) 'Feedstock for the Petrochemical Industry'. Available at: https://icrier.org/pdf/working_paper_271.pdf (Accessed: 23 October 2016).

Ren, T. and Patel, M. (2009) 'Basic petrochemicals from natural gas, coal and biomass: Energy use and CO_2 emissions', *Resources, Conservation and Recycling*, 53(9), pp. 513–528. doi: 10.1016/j.resconrec.2009.04.005.

Ringrose, P., Mathieson, A., Wright, W., Selama, F., Hansen, O., Bissell, R., Saoula, N. and Midgley, J. (2013) 'The In Salah CO_2 Storage Project: Lessons Learned and Knowledge Transfer', *Energy Procedia*, 37, pp. 6226–6236. doi: 10.1016/j.egypro.2013.06.551.

Roberts, T. and Mander, S. (2011) 'Assessing public perceptions of CCS: Benefits, challenges and methods', *Energy Procedia*, 4, pp. 6307–6314. doi:10.1016/j.egypro.2011.02.646.

Rodríguez, N., Murillo, R. and Abanades, J. (2012) 'CO_2 capture from cement plants using oxyfired precalcination and/ or calcium looping', *Environmental Science and Technology*, 46(4), pp. 2460–2466. doi: 10.1021/es2030593.

Romeo, L., Catalina, D., Lisbona, P., Lara, Y., Martinez, A (2011) 'Reduction of greenhouse gas emissions by integration of cement plants: power plants and CO_2 capture systems', *Greenhouse Gases Science and Technology*, 1(1), pp. 72–82. doi:10.1002/ghg3.5.

Roos, C. (2009) 'Solar Electric System Design'. Available at: http://www.energy.wsu.edu/Documents/SolarPVforBuildersOct2009.pdf (Accessed: 19 August 2016).

Rubin, E. and Zhai, H. (2012) 'The Cost of Carbon Capture and Storage for Natural Gas Combined Cycle Power Plants', *Environmental Science & Technology*, 46(6), pp. 3076–3084. doi: 10.1021/es204514f.

Rubin, E., Davison, J. and Herzog, H. (2015) ‘The cost of CO_2 capture and storage’, *International Journal of Greenhouse Gas Control*, 40, pp. 378–400. doi: 10.1016/j.ijggc.2015.05.018.

Rubin, E., Mantripragada, H., Marks, A., Versteeg, P., Kitchin, J. (2012) ‘The outlook for improved carbon capture technology’, *Progress in Energy and Combustion Science*, 38, pp. 630–671. doi:10.1016/j.pecs.2012.03.003.

Russial, T. (2011) ‘Carbon capture and storage –legal and regulatory framework’. Available at: https://usea.org/sites/default/files/ccc17012011_Carbon%20capture%20and%20storage%20-%20legal%20and%20regulatory%20framework_ccc179.pdf (Accessed: 16 December 2018).

Sandberg, H., Lagneborg, R., Lindblad, B., Axelsson, H. and Bentell, L. (2001) ‘CO_2 emissions of the Swedish steel industry’, *Scandinavian Journal of Metallurgy*, 30(6), pp. 420–425. doi: 10.1034/j.1600-0692.2001.300611.x.

Sarbring, A. (2014) *A Carbon Footprint Assessment on Construction and Maintenance Operations for the Port of Gothenburg.* Master thesis within the industrial Ecology programme. Chalmers University of Technology.

Sarker, T., Corradetti, R. and Zahan, M. (2013) ‘Energy Sources and Carbon Emissions in the Iron and Steel Industry Sector in South Asia’, *International Journal of Energy Economics and Policy*, 3(1), pp. 30–42. ISSN: 2146-4553.

Sattary, S. and Thorpe, D. (2012) ‘Optimizing Embodied Energy of Building Construction Through Bioclimatic Principles’. Available at: https://www.arcom.ac.uk/-docs/proceedings/ar2012-1401-1411_Sattary_Thorpe.pdf (Accessed: 7 July 2018).

Satter, A., Iqbal, G., and Buchwalter, J. (2008) *Practical Enhanced Reservoir Engineering: Assisted With Simulated Software*. Tulsa, Olkla: PennWell Corp.

Savsar, M., Alardhi, M. and Almazrouee, A. (2012) ‘Capacity and Availability Analysis of Power Plants in Kuwait’. Available at: http://ieomsociety.org/ieom2012/pdfs/380.pdf (Accessed: 18 April 2017).

SCCS (2015) *Global CCS Map*. Available at: https://www.sccs.org.uk/expertise/global-ccs-map (Accessed: 23 October 2018).

Schakel, W., Oreggioni, G., Singh, B., Strømman, A. and Ramírez, A. (2016) 'Assessing the techno environmental performance of CO_2 utilization via dry reforming of methane for the production of dimethyl ether', *Journal of CO_2 Utilization*, 16, pp. 138–149. doi: 10.1016/j.jcou.2016.06.005.

Scholes, C., Ho, M., Aguiar, A., Wiley, D., Stevens, G. and Kentish, S. (2014) 'Membrane gas separation processes for CO_2 capture from cement kiln flue gas', *International Journal of Greenhouse Gas Control*, 24, pp. 78–86. doi: 10.1016/j.ijggc.2014.02.020.

Serpa, J., Morbee, J. and Tzimas, E. (2011) *Technical and economic characteristics of a CO_2 transmission pipeline infrastructure*. Available at: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/technical-and-economic-characteristics-co2-transmission-pipeline-infrastructure (Accessed: 5 May 2019).

Shabbir, I. and Mirzaeian, M. (2017) 'Carbon Emissions Reduction Potentials in Pulp and Paper Mills by Applying Cogeneration Technologies', *Energy Procedia*, 112, pp. 142–149. doi: 10.1016/j.egypro.2017.03.1075.

Sharma, S. (2007) Personal communication. Kuwait Oil Company (KOC), Reservoir Management Group.

Shen, L., Gao, T., Zhao, J., Wang, L., Wang, L., Liu, L., Chen, F. and Xue, J. (2014) 'Factory-level measurements on CO_2 emission factors of cement production in China', *Renewable and Sustainable Energy Reviews*, 34, pp. 337–349. doi: 10.1016/j.rser.2014.03.025.

Shokrollahi, A., Arabloo, M., Gharagheizi, F. and Mohammadi, A., (2013) 'Intelligent model for prediction of CO_2- Reservoir oil minimum miscibility pressure', *Fuel*, 112, pp. 375–384. doi: 10.1016/j.fuel.2013.04.036.

Skårman, T. and Gustafsson, T. (2013) 'Revision of estimated greenhouse gas emissions for integrated iron and steel production on Climate Change'. Available at: https://www.diva-portal.org/smash/get/diva2:1188121/FULLTEXT01.pdf (Accessed: 12 October 2017).

Smith, M., Campbell, D., Mackay, E., and Polson, D. (2012) *CO_2 Aquifer Storage Site Evaluation and Monitoring, Understanding the Challenges of CO_2 Storage: Results of CASSEM Project*. Available at: http://nora.nerc.ac.uk/id/eprint/17527/1/CASSEM_Comp_12_12_11.pdf (Accessed: 4 June 2019).

Steeneveldt, R., Berger, B. and Torp, T. (2006) 'CO_2 capture and storage: Closing the knowing-doing gap', *Chemical Engineering Research and Design*, 84(9), pp. 739–763. doi: 10.1205/cherd05049.

Stockle, M., Bullen, T. (2008) 'Integrating refinery CO_2 reduction strategies into your refinery', *ERTC Sustainable Refining Conference*, Brussels, March 31, Belgium.

Tang, Y. and You, F. (2018) 'Life cycle environmental and economic analysis of pulverized coal oxy-fuel combustion combining with calcium looping process or chemical looping air separation', *Journal of Cleaner Production*, 181, pp.271 –292. doi: 10.1016/j.jclepro.2018.01.26.

Teir, S., Hetland, J., Lindeberg, E., Torvanger, A., Buhr, K., Koljonen, T., Gode, J., Onarheim, K., Tjernshaugen, A., Arasto, A., Liljeberg, M., Lehtilä, A., Kujanpää, L. and Nieminen, M. (2010) 'Potential for carbon capture and storage (CCS) in the Nordic region'. Available at: https://www.sintef.no/globalassets/project/nordiccs/vtt_t2556.pdf (Accessed: 18 March 2018).

Thomson, D., FCMA, C., Khare, A. (2008) 'Carbon Capture and Storage (CCS) Deployment – Can Canada Capitalize on Experience ?', *Journal of Technology Management & Innovation*, 3(4), pp. 111–118. doi: 10.4067/S0718-27242008000200009.

Tian, S., Li, K., Jiang, J., Chen, X. and Yan, F. (2016) 'CO_2 abatement from the iron and steel industry using a combined Ca-Fe chemical loop', *Applied Energy*, 170, pp. 345 –352. doi: 10.1016/j.apenergy.2016.02.120.

Timilsina, G. and Shrestha, A. (2009) 'Transport sector CO_2 emissions growth in Asia: Underlying factors and policy options', *Energy Policy*, 37(11), pp. 4523–4539. doi: 10.1016/j.enpol.2009.06.009.

Trading economic (2019) *Kuwait GDP per capita*. Available at: https://tradingeconomics.com/kuwait/gdp-per-capita (Accessed: 23 January 2019).

Tsai, I. (2014) 'CCS Regulation in Gulf Cooperation Council (GCC): Current Progress & Future Perspectives'. Available at: https://iea.blob.core.windows.net/assets/imports/events/3/1.3_Tsai.pdf (Accessed: 6 July 2018).

United States National Energy Technology Laboratory (NETL) (2007) ‘Carbon Sequestration Atlas of the United States and Canada’. Available at: http://www.precaution.org/lib/carbon_sequestration_atlas.070601.pdf (Accessed: 26 July 2017).

United States National Technology Energy Laboratory (NETL) (2008) ‘Development of baseline data and analysis of life cycle greenhouse gas emission of petroleum-based fuels’. Available at: http://www.nata.aero/data/files/gia/environmental/bllcghg2005.pdf (Accessed: 11 July 2018).

United Nation Climate Change (2015) *Kuwait Submits its Climate Action Plan Ahead of 2015 Paris Agreement*. Available at: https://unfccc.int/news/kuwait-submits-its-climate-action-plan-ahead-of-2015-paris-agreement (Accessed: 18 March 2017).

United Nations Enviornmental Programme (UNEP) (2011) *Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal*. Available at: http://www.basel.int/?tabid=4499 (Accessed: 18 July 2021).

United Nations Enviornmental Programme (UNEP) (2014) *Kuwait Regional Convention for Cooperation on the Protection of the Marine Environment from Pollution (Kuwait Convention)*. Available at: https://www.biodiversitya-z.org/content/kuwait-regional-convention-for-cooperation-on-the-protection-of-the-marine-environment-from-pollution-kuwait-convention (Accessed: 18 April 2021).

United Nations Environment Programme (UNEP) (2015) ‘The emissions gap report 2015’. Available at: https://www.unenvironment.org/resources/emissions-gap-report-2015 (Accessed: 16 November 2017).

United Nations Environment Programme (UNEP) (2021) ‘Basel convention, on the control of transboundary movement of hazardous waste and their disposal’. Available at: https://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf (Accessed: 4 May 2021).

United Nations Framework Convention on Climate Change (UNFCCC) (2019) *Integrated Assessment Models (IAMs) and Energy-Environment-Economy (E3) models*. Available at: https://unfccc.int/topics/mitigation/workstreams/response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models (Accessed: 6 September 2019).

United Nations Framework Convention on Climate Change (UNFCCC) (2007) 'Uniting on climate'. Available at: http://unfccc.int/resource/docs/publications/unitingonclimate_eng.pdf (Accessed: 19 May 2016).

United Nations Framework Convention on Climate Change (UNFCCC) (2021a) *What is the Kyoto Protocol?*. Available at: https://unfccc.int/kyoto_protocol (Accessed: 19 April 2021).

United Nations Framework Convention on Climate Change (UNFCCC) (2021b) *Kuwait*. Available at: https://unfccc.int/node/61094 (Accessed: 7 March 2021).

United Nations Industrial Development Organization (2010) 'Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report Working Paper'. Available at: https://www.unido.org/sites/default/files/2010-12/synthesis_final_0.pdf (Accessed: 15 July 2017).

United Nations Treaty Collection (2021) *United Nations Convention on the Law of the Sea*. Available at: https://treaties.un.org/PAGES/ViewDetailsIII.aspx?src=TREATY&mtdsg_no=XXI-6&chapter=21&Temp=mtdsg3&clang=_en (Accessed: 6 April 2021).

United States Environmental Protection Agency (EPA) (2002) *National Emissions Inventory (NEI)*. Available at: https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei (Accessed: 3 September 2016).

United States Environmental Protection Agency (EPA) (2012) 'Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry'. Available at: https://www.epa.gov/sites/production/files/2016-11/documents/iron-steel-ghg-bact-2012.pdf (Accessed: 19 February 2018).

United States Environmental Protection Agency (EPA) (2014) 'Greenhouse Gas Emissions from a Typical Passenger Vehicle'. Available at: https://planning.lacity.org/eir/ConventionCntr/DEIR/files/references/United%20States%20EPA%20Greenhouse%20Gas%20Emissions%20from%20a%20Typical%20Passenger%20Vehicle.pdf (Accessed: 8 April 2018).

United States Environmental Protection Agency (EPA) (2016) 'Air Emissions Management in Kuwait Oil Company'. Available at: www.epa.gov/sites/production/files/2016-

04/documents/tue4emissionmanagementinkoc.pdf (Accessed: 8 June 2020).

United States Environmental Public Authority (EPA) (2015) ‘Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems’. Available at: https://www.epa.gov/sites/production/files/2015-07/documents/fuel_and_carbon_dioxide_emissions_savings_calculation_methodology_for_combined_heat_and_power_systems.pdf (Accessed: 23 April 2019).

Usman, Iskandar, U., Sugihardjo, Lastiadi, S. (2014) ‘A Systematic Approach to Source-Sink Matching for CO_2 EOR and Sequestration in South Sumatera’, *Energy Procedia*, 63, pp. 7750–7760. doi: 10.1016/j.egypro.2014.11.809.

Van Alphen, K., Hekkert, M. and Turkenburg, W. (2009) ‘Comparing the development and deployment of carbon capture and storage technologies in Norway, the Netherlands, Australia, Canada and the United States-An innovation system perspective’, *Energy Procedia*, 1(1), pp. 4591–4599. doi: 10.1016/j.egypro.2009.02.279.

Van Bergen, F., Gale, J., Damen, K. and Wildenborg, A. (2004) ‘Worldwide selection of early opportunities for CO_2-enhanced oil recovery and CO_2-enhanced coal bed methane production’, *Energy*, 29(9–10), pp. 1611–1621. doi: 10.1016/j.energy.2004.03.063.

Van Straelen, J., Geuzebroek, F., Goodchild, N., Protopapas, G. and Mahony, L. (2010) ‘CO_2 capture for refineries, a practical approach’, *International Journal of Greenhouse Gas Control*, 4(2), pp. 316–320. doi: 10.1016/j.ijggc.2009.09.022.

Voldsund, M., Jordal, K. and Anantharaman, R. (2016) ‘Hydrogen production with CO_2 capture’, *International Journal of Hydrogen Energy*, 41(9), pp. 4969–4992. doi: 10.1016/j.ijhydene.2016.01.009.

Wang, J., Kang, J., Liu, L., Nistor, I., Wei, Y. (2020) ‘Research trends in carbon capture and storage: A comparison of China with Canada’, *International Journal of Greenhouse Gas Control*, 97, pp. 103018. doi:10.1016/j.ijggc.2020.103018.

Wang, M., Lawal, A., Stephenson, P., Sidders, J., and Ramshaw, C. (2011) ‘Post-combustion CO_2 capture with chemical absorption: A state-of-the-art review’, *Chemical Engineering Research and Design*, 89, pp.1609–1624. doi:10.1016/j.cherd.2010.11.005.

Weydahl, T., Jamaluddin, J., Seljeskog, M. and Anantharaman, R. (2013) Pursuing the pre-combustion CCS route in oil refineries - The impact on fired heaters', *Applied Energy*, 102, pp. 833–839. doi: 10.1016/j.apenergy.2012.08.044.

Wheeler, F .and Collodi, G. (2009) 'Hydrogen Production via Steam Reforming with CO_2 Capture'. Available at: https://www.aidic.it/CISAP4/webpapers/7Collodi.pdf (Accessed: 23 June 2016).

Wilberforce, T., Baroutaji, A., Soudan, B., Al-Alami, A., Olabi, A. (2019) 'Outlook of carbon capture technology and challenges', *Science of the Total Environment*, 657, pp.56–72. doi:10.1016/j.scitotenv.2018.11.424.

Witkowski, A., Majkut, M., Rusin, A. and Rulik, S. (2015) 'Advances in Carbon Dioxide Compression and Pipeline Transportation Processes'. Available at: https://www.researchgate.net/publication/278406042_Advances_in_Carbon_Dioxide_Compression_and_Pipeline_Transportation_Processes (Accessed: 18 September 2017).

World Bank Report (WBR) (2006) 'World development indicators'. Available at: https://openknowledge.worldbank.org/handle/10986/8151(Accessed: 28 February 2018).

World Bank Report (WBR) (2018) *CO_2 emissions (metric tons per capita) - Kuwait*. Available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=KW (Accessed: 6 August 2019).

World Business Council for Sustainable Development (2002) 'Toward A Sustainable Cement Industry Trends, Challenges, and Opportunities in China's Cement Industry'. Available at: http://ficem.org/CIC-descargas/Suiza/CSI/Towards-a-Sustainable-Cement-Industry.pdf (Accessed: 5 July 2018).

World Health Organization (WHO) (2016) 'Climate and Health, the country profile- 2015, Kuwait'. Available at: https://apps.who.int/iris/bitstream/handle/10665/246149/WHO-FWC-PHE-EPE-15.24-eng.pdf?sequence=1&isAllowed=y (Accessed: 18 December 2018).

World Population Review (2020) *Kuwait population*. Available at:

https://worldpopulationreview.com/countries/kuwait-population (Accessed: 23 July 2020).

World Steel Association (2011) *Steel Statistical Yearbook 2011*. Available at: https://www.worldsteel.org/(Accessed: 28 December 2018).

Wortman, D. and Echo-Hawk, L (1999) 'Photovoltaic and Solar-Thermal Technologies in Residential Building Codes, Tackling Building Code Requirements to Overcome the Impediments to Applying New Technologies'. Available at: https://www.nrel.gov/docs/fy99osti/26579.pdf (Accessed: 26 July 2019).

Yan, Y., Wang, K., Clough, P., Anthony, E. (2020) 'Developments in calcium/chemical looping and metal oxide redox cycles for high-temperature thermochemical energy storage: A review', *Fuel Processing Technology*, 199, pp. 106–280. doi:10.1016/j.fuproc.2019.106280.

Yessian, K., DeLaquil, P., Merven, B., Gargiulo, M., Goldstein, G. (2013) 'Economic analysis of clean energy options for Kuwait'. Available at: https://www.decisionwaregroup.com/assets/kuwait_economic-analysis-of-nuclear-and-renewable-energy-options.pdf (Accessed: 20 May 2016).

Zakarya, G., Mostefa, B., Abbes, S. Seghir,and G. (2015) 'Factors Affecting CO_2 Emissions in the BRICS Countries: A Panel Data Analysis', *Procedia Economics and Finance*, 26, pp. 114–125. doi: 10.1016/S2212-5671(15)00890-4.

Zakuciová, K., Rocha, J. L. and Ko, V. (2015) 'Life Cycle Assessment Overview of Carbon Capture and Storage Technologies'. Available at: https://hitecarlo.vscht.cz/files/uzel/0014795/i0rMLk3OzC9LjE8rzclRKEmtKIkPdnUNNjIwNAMA.pdf?redirected (Accessed: 20 March 2016).

Zbib, S. and Farran, R. (2011) 'Kuwait Cement Industry'. Available at: http://content.argaam.com.s3-eu-west-1.amazonaws.com/5ed6387b-9c06-47d5-b9a5-014d35e03b95.pdf (Accessed: 11 November 2018).

Zero Emission Platform (ZEP) (2011) 'The Costs of CO_2 Capture, Transport and Storage'. Available at: https://www.globalccsinstitute.com/archive/hub/publications/17011/costs-co2-capture-transport-and-storage.pdf (Accessed: 14 December 2016).

Zero Emission Platform (ZEP) (2013) 'CO_2 Capture and Storage (CCS) in energy intensive industries: An indispensable route to an EU low-carbon economy'. Available at:

https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-report_-CCS-in-industry-1.pdf (Accessed: 9 May 2018).

Zero Waste Scotland (2011) 'The water and carbon footprint of household food and drink waste in the UK'. Available at: http://www.wrap.org.uk/sites/files/wrap/Water_and_Carbon_Footprint_Report_Scottish_Summary.pdf (Accessed: 12 August 2018).

Zhang, B., Wang, Z., Yin, J. and Su, L. (2012) 'CO_2 emission reduction within Chinese iron & steel industry: Practices, determinants and performance', *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2012.04.012.

Zhang, D., Liu, P., Ma, L. and Ni, W. (2012) 'A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation', *Computers and Chemical Engineering*. doi: 10.1016/j.compchemeng.2011.09.001.

Zhang, S., Shen, Y., Wang, L., Chen, J., Lu, Y. (2019) 'Phase change solvents for post-combustion CO_2 capture: Principle, advances, and challenges', *Applied Energy,* 239, pp.876 – 897. doi: 10.1016/j.apenergy.2019.01.242.

Zhou, W., Jiang, D., Chen, D., Griffy-Brown, C., Jin, Y. and Zhu, B., (2016) 'Capturing CO_2 from cement plants: A priority for reducing CO_2 emissions in China', *Energy*, 106, pp. 464–474. doi: 10.1016/j.energy.2016.03.090.

Appendix

Appendix A. Kuwait air pollutants

Appendix A.1 Air pollutants standards for the State of Kuwait

No.	Pollutant	Averaging Time	Limit	Classification Method
1	SO_2	Hour	75 ppb	A
		24 Hour	19 ppb	B
2	NO_2	Hour	100 ppb	A
		Annual	21 ppb	C
3	CO	Hour	35 ppm	D
4	O_3	8 Hour	70 ppb	A
5	Pb	Quarterly Average	0.15 $\mu g/m^3$	C
6	PM_{10}	24 Hour	350 $\mu g/m^3$	A
7	$PM_{2.5}$	24 Hour	75 $\mu g/m^3$	A

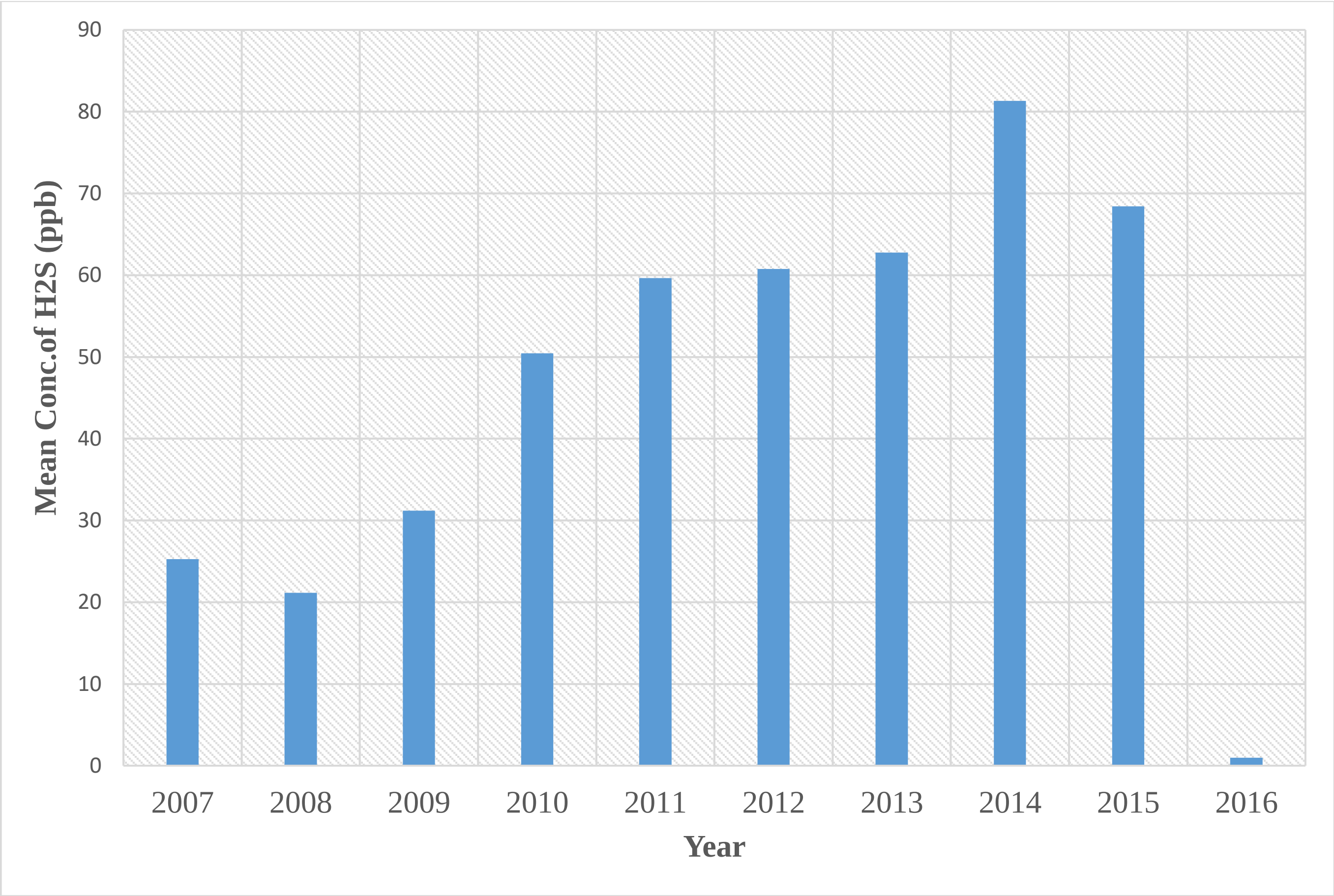
A- 99th percentile of maximum concentration over one year.

B- Not exceed more than 1 time per year in the same location.

C- Not to exceed.

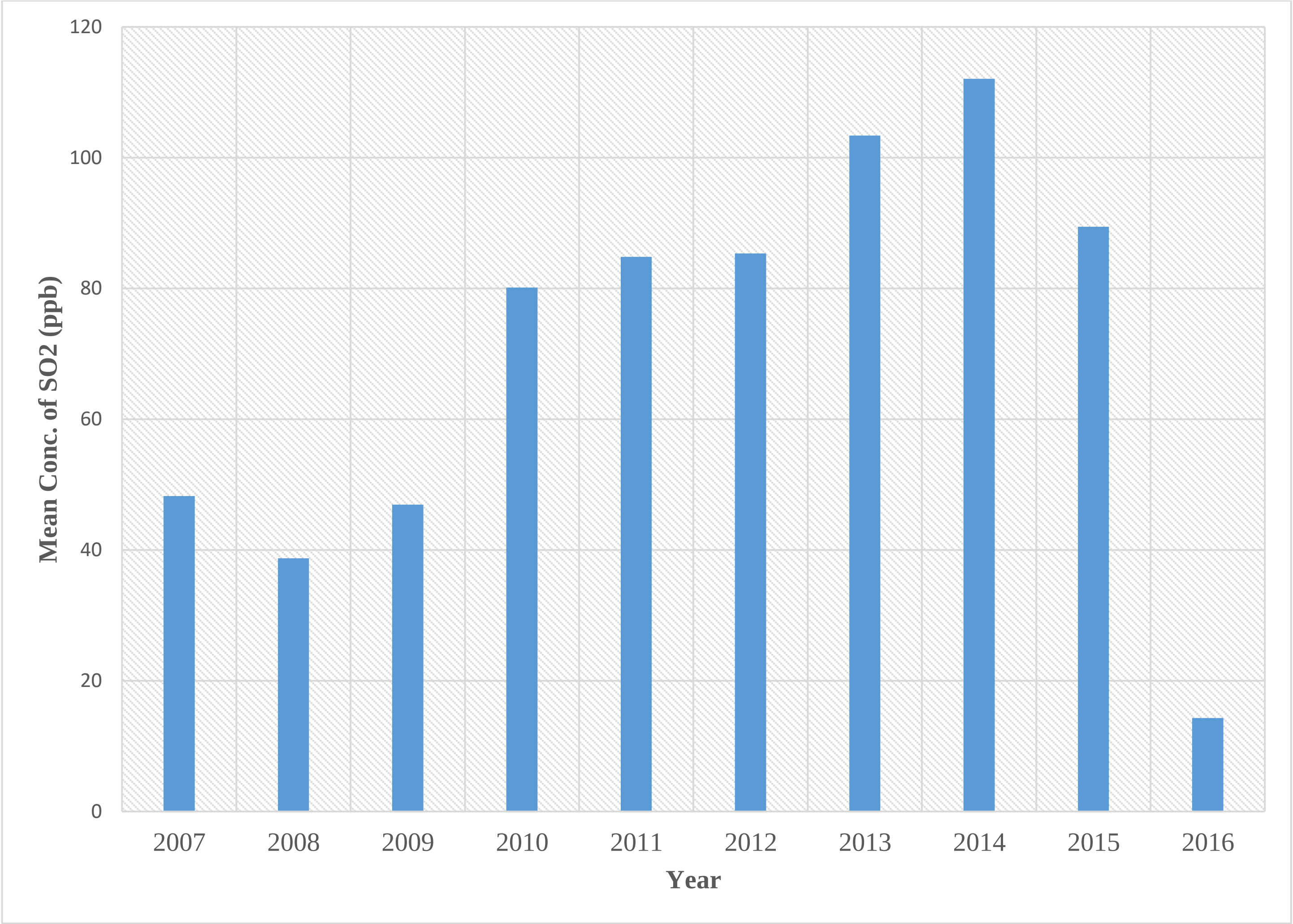
D- Not exceed more than 3 times per year in the same location.

Source: (KEPA, 2019)



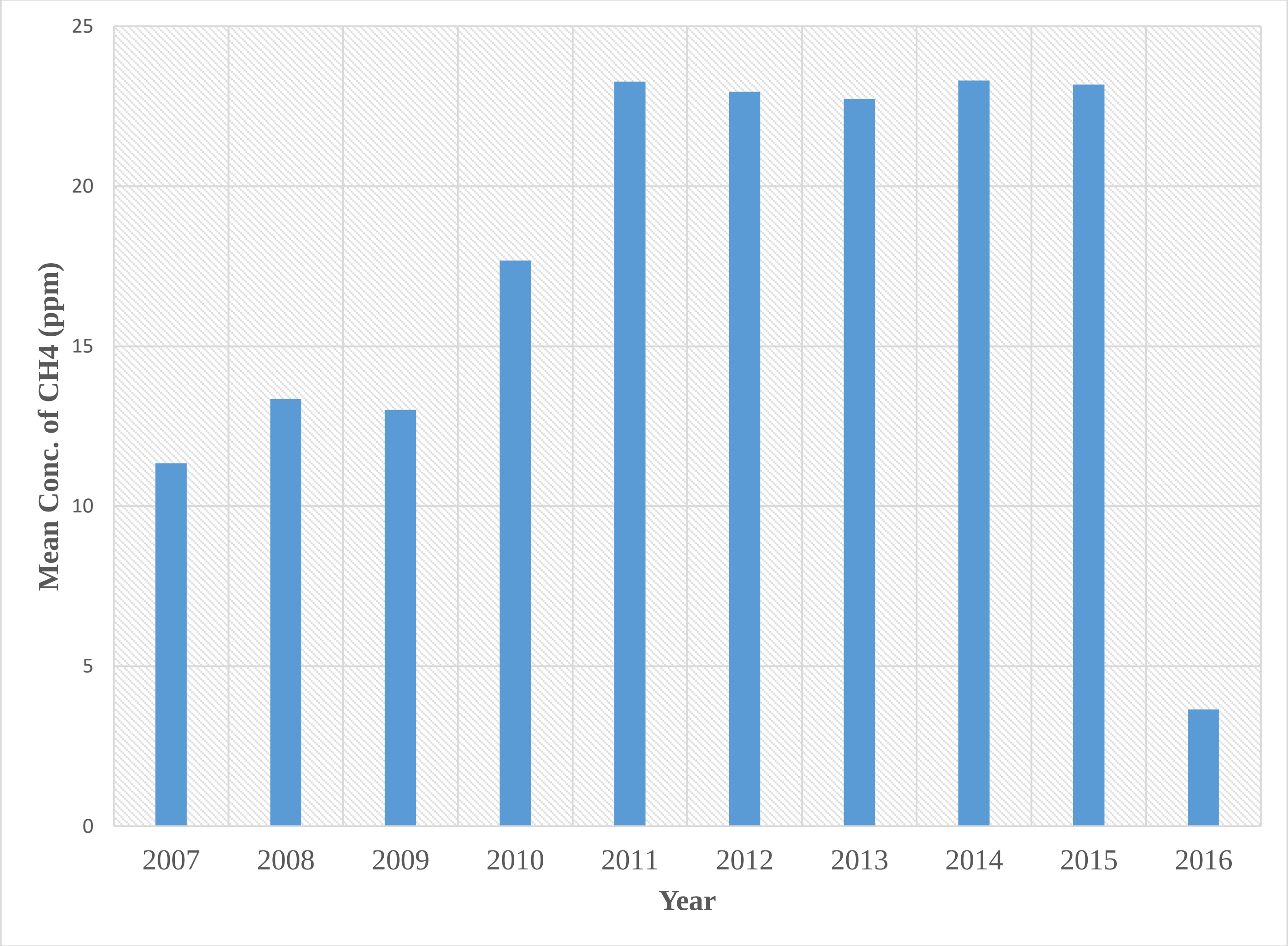
Source: (KEPA, 2019)

Appendix A.2 Mean concentration of H_2S (ppb) in the State of Kuwait during 2007 to 2016



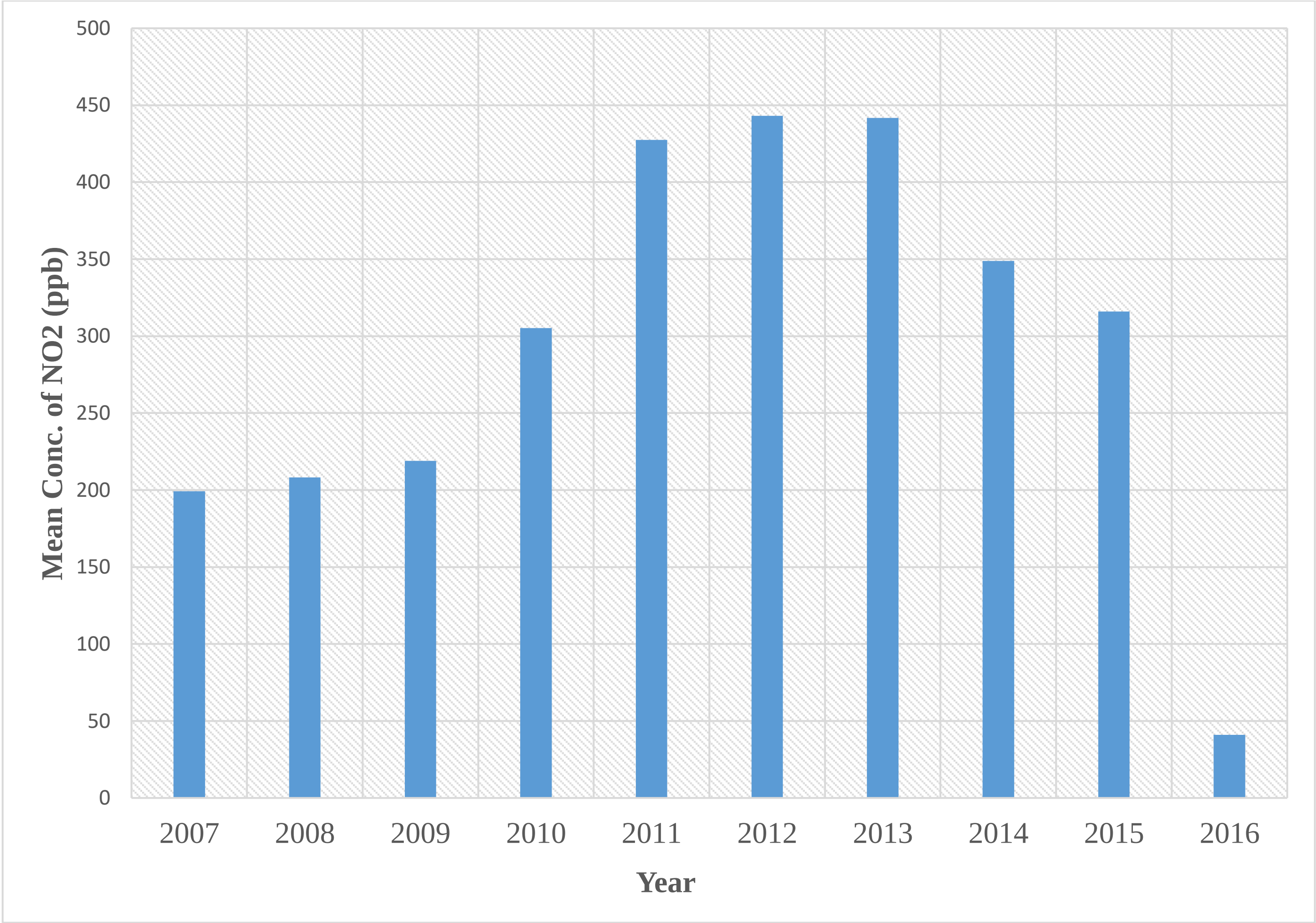
Source: (KEPA, 2019)

Appendix A.3 Mean concentration of SO_2 (ppb) in the State of Kuwait during 2007 to 2016



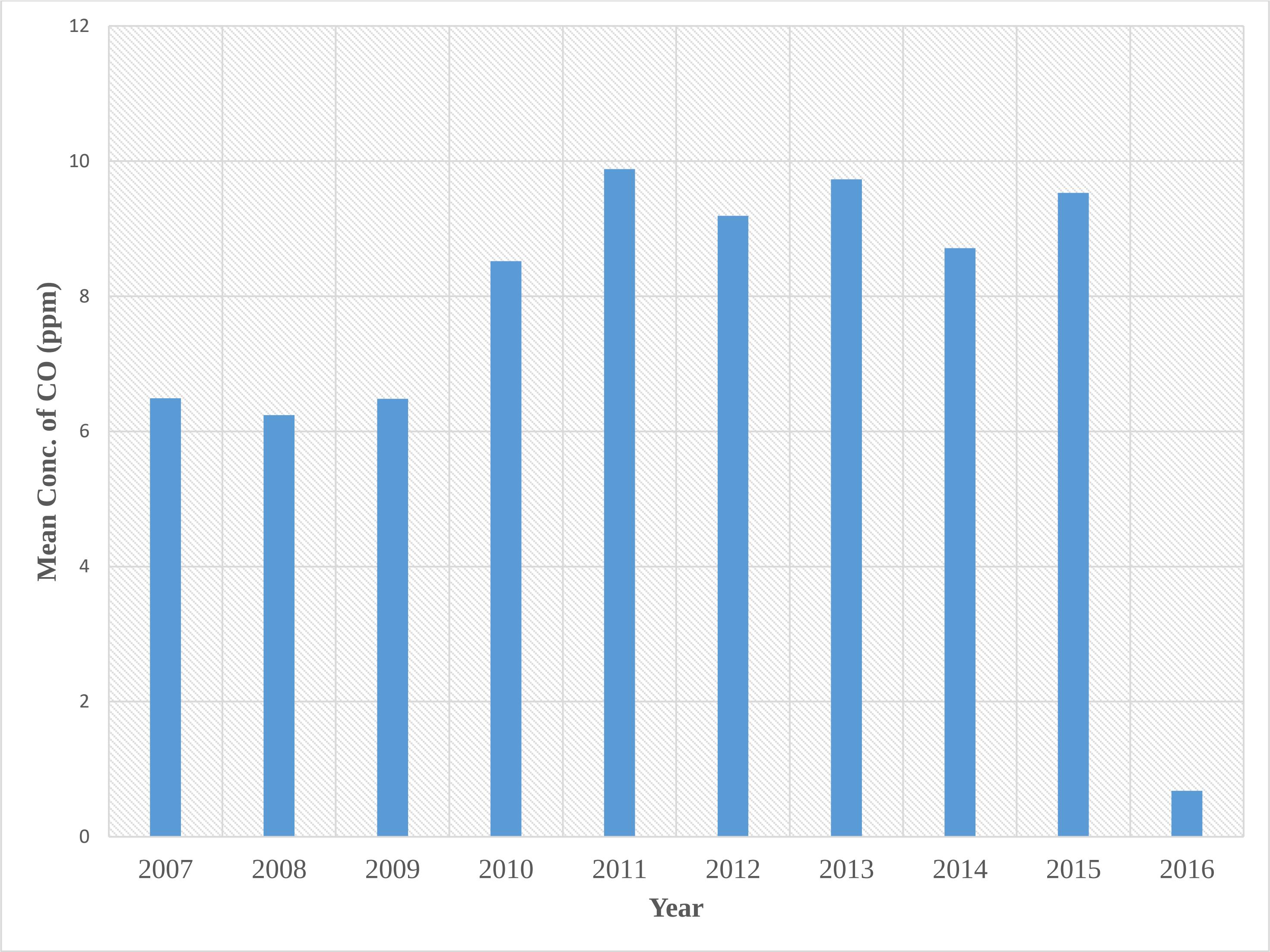
Source: (KEPA, 2019)

Appendix A.4 Mean concentration of CH_4 (ppm) in the State of Kuwait during 2007 to 2016



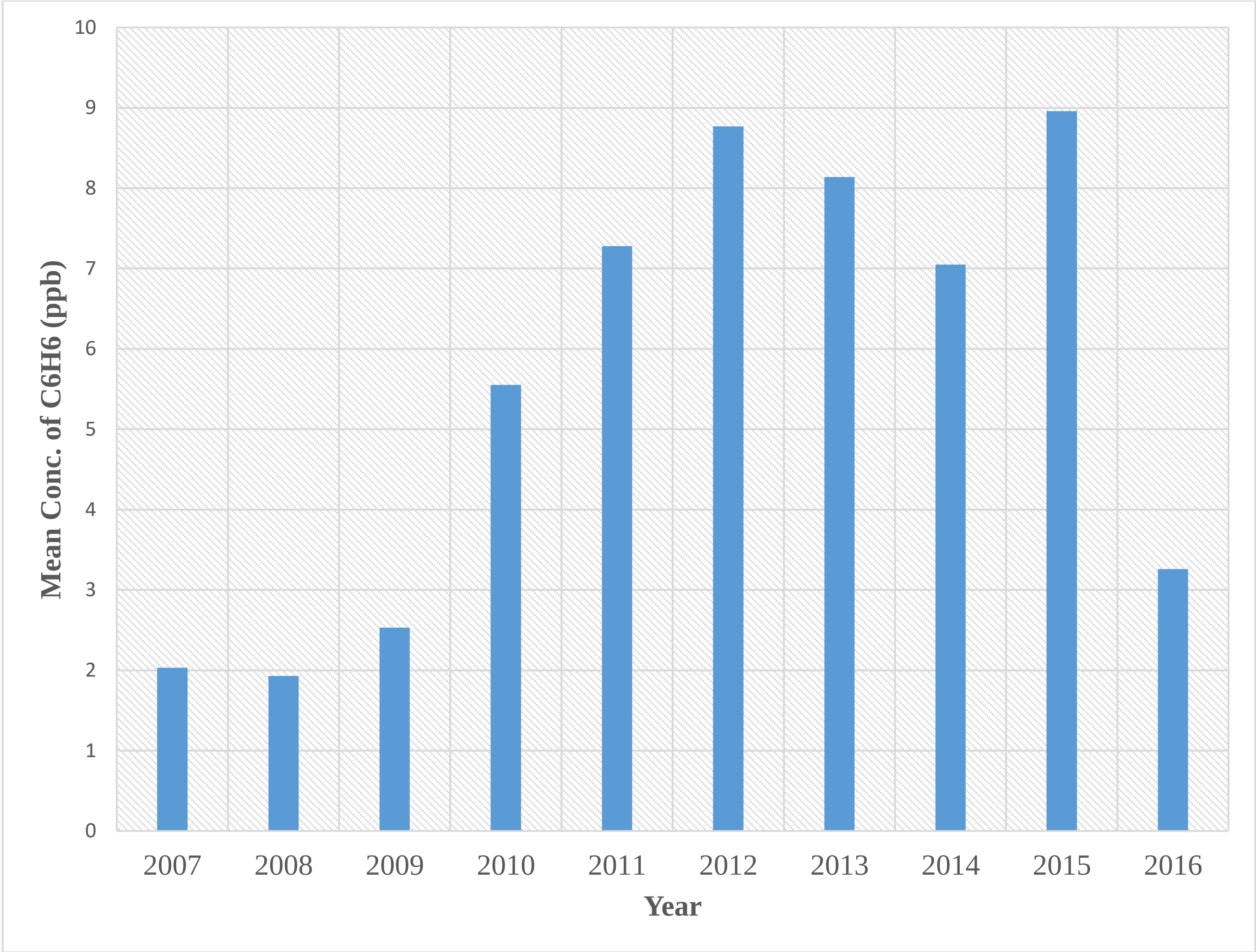
Source: (KEPA, 2019)

Appendix A.5 Mean concentration of NO_2 (ppb) in the State of Kuwait during 2007 to 2016



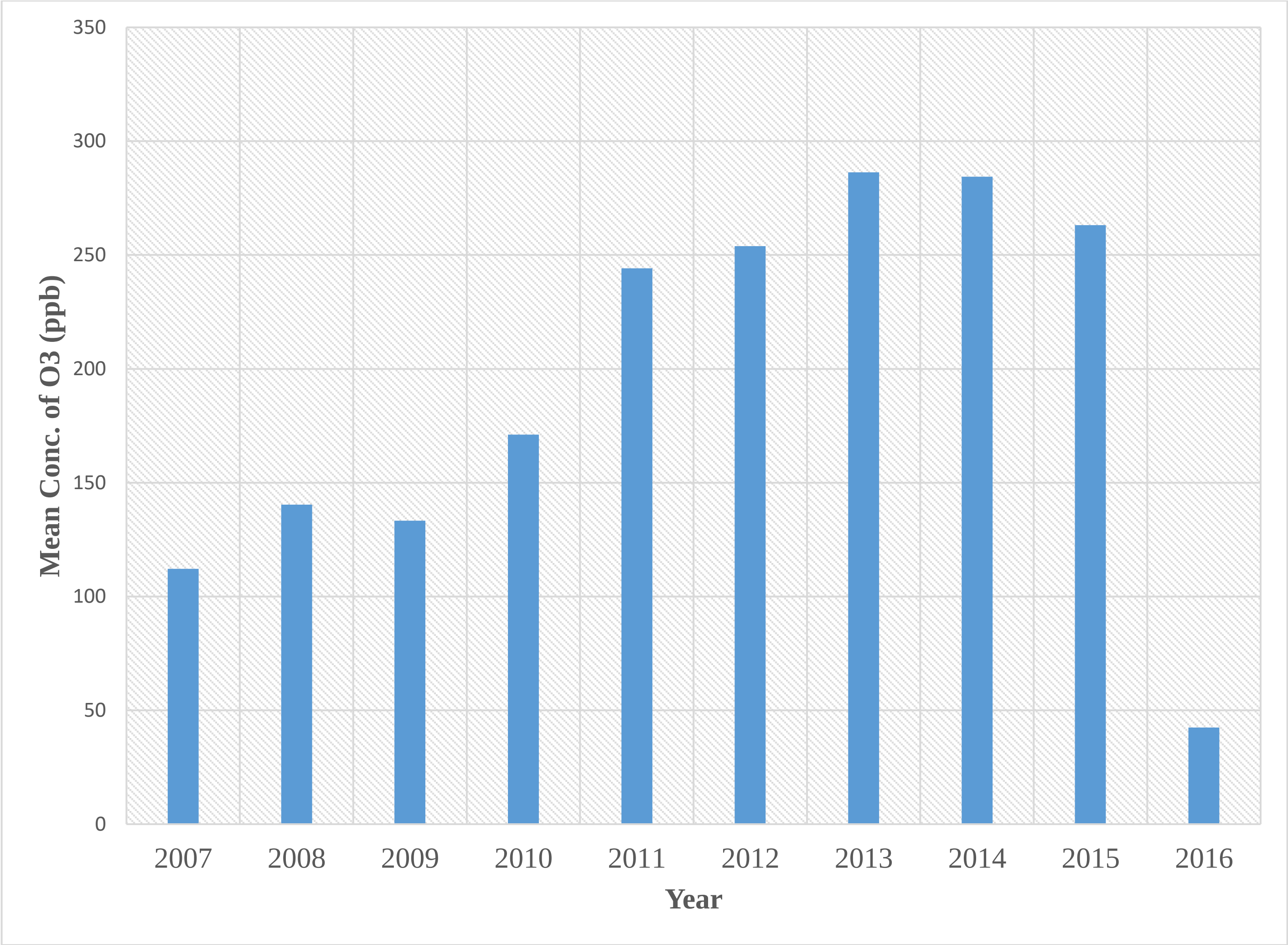
Source: (KEPA, 2019)

Appendix A.6 Mean concentration of CO (ppm) in the State of Kuwait during 2007 to 2016



Source: (KEPA, 2019)

Appendix A.7 Mean concentration of C_6H_6 (ppb) in the State of Kuwait during 2007 to 2016



Source: (KEPA, 2019)

Appendix A.8 Mean concentration of O_3 (ppb) in the State of Kuwait during 2007 to 2016

Appendix B. Group Discussion

Appendix B.1 Discussion Question

Basic information

1- How would you describe the production process in your facility?
2- What is the advantage of technology applied in your facility in compared to the other technologies?
3- What are the optimum operating conditions for your facility?
4- Which fuel type used in your facility?
5- Which type of distributed energy system used in your facility (e.g. CHP plants, boilers and hydrogen plants)?
6- What is the space available in the facility layout? And to what extent can this space be used?

The carbon footprint

1- What are the main emission sources of CO_2 in your facility?
2- What is the concentration and partial pressure of CO_2 flow gas from these sources?
3- What is the type and percent of impurities present in the flowing gas?
4- Do you produce a yearly report addressing the carbon footprint of your facility?

Carbon dioxide abatement practices

1- What is the current carbon abatement strategy utilised in your facility?
2- What is your long-term objective for carbon abatement?
3- If Environmental Public Authority (EPA) introduces a carbon tax, would you think of constructing a carbon capture unit in your facility?

Post-combustion- if applicable

1- What are the units that produce excess energy?
2- What are the technical modifications required to redirect these energies for post-combustion capture units?

Oxy-fuel combustion- if applicable

1- What are the technical and spatial constraints of deploying the Air Separation Unit (ASU) in your facility?

2- Which units in your facility need to be modified to work on full oxy-fuel combustion mode?
3- From a technical perspective, can you recycle back the CO_2 to the generator to reduce the combustion temperature?

Pre-combustion - if applicable

1- Can hydrogen be used as the main fuel in your utilities? If no, what are the technical barriers?

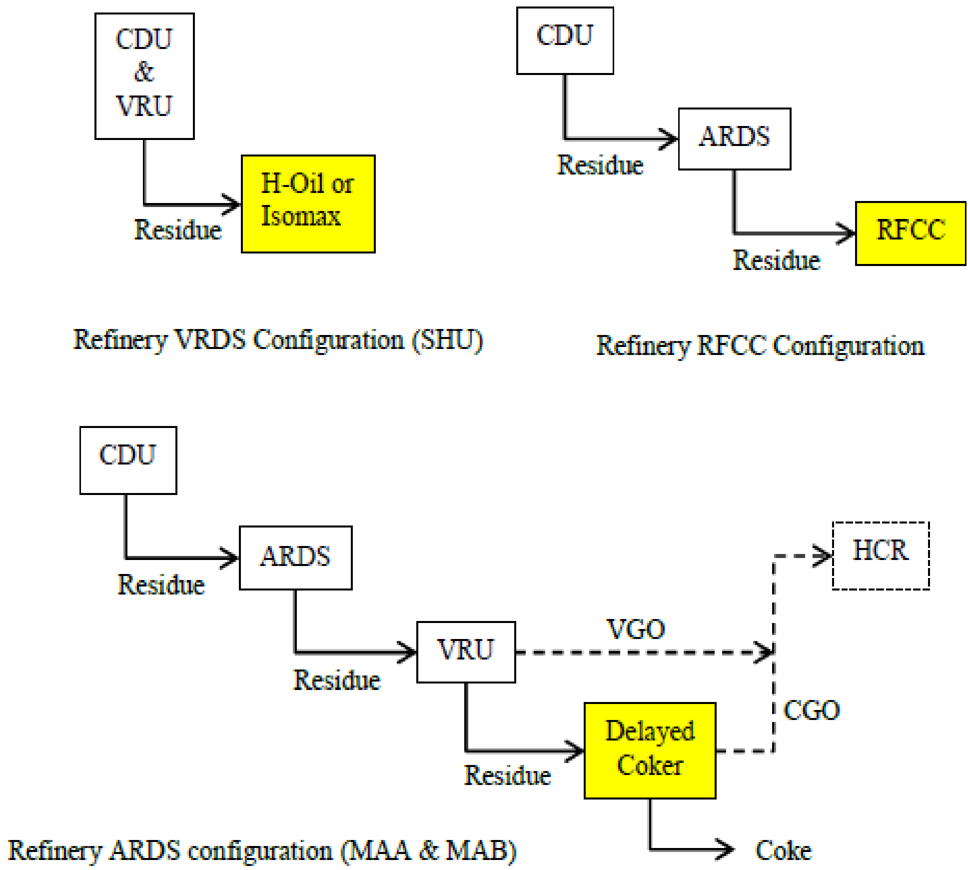
The risks associated with deploying carbon capture technologies

1- In your opinion, what are the potential risks (health, safety, or environmental) associated with deploying carbon capture technologies in your facility?
2- What are your safety procedures to deal with these risks?

Utilization pathways

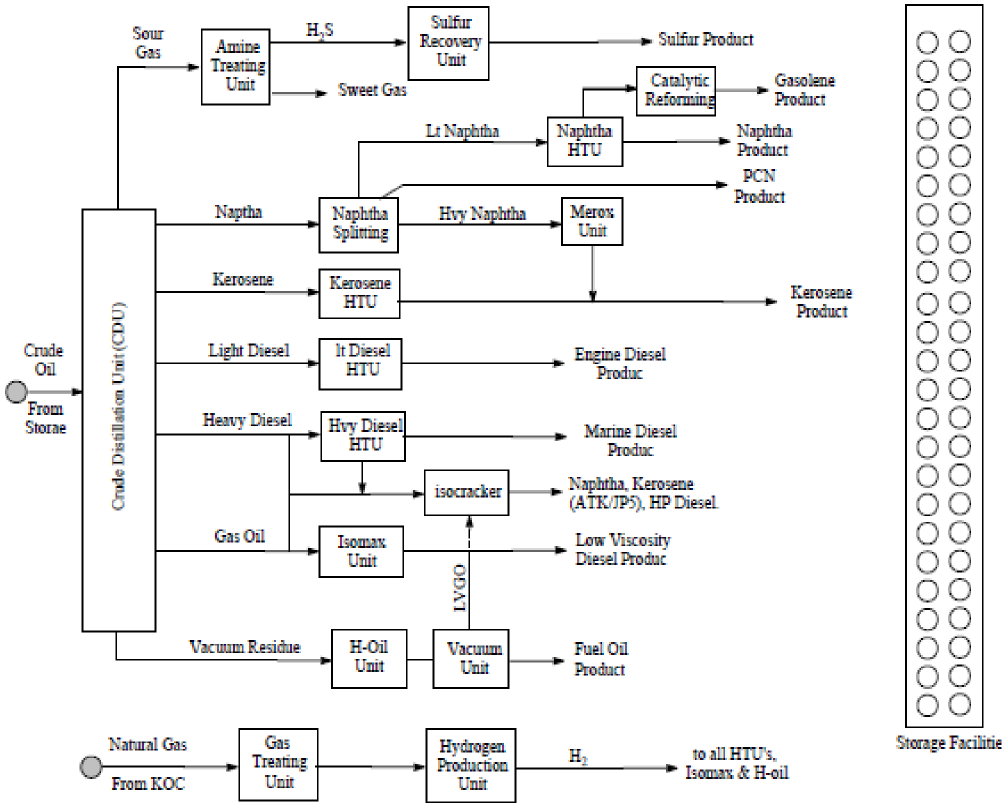
1- Can you utilize the captured CO_2 in your production pathway?
2- Can your current pipeline be modified to transport CO_2 for the central treatment location in the future?

Appendix C. Kuwait refineries data obtained from the discussion group meeting



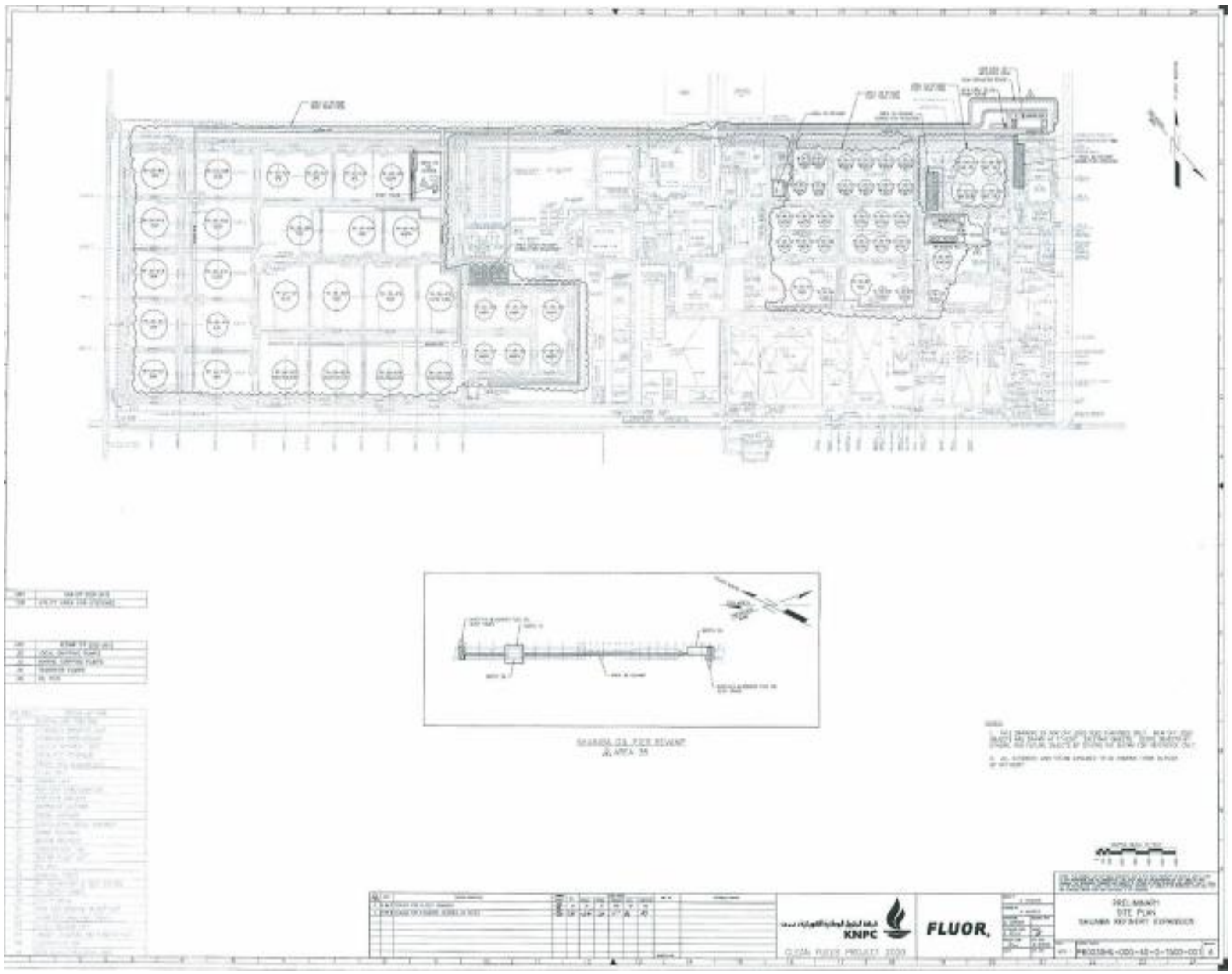
Source: (Alaimi, 2018)

Appendix C.1 The three basic refinery configurations



Source: (Alaimi, 2018)

Appendix C.2 Shuaiba Refinery Layout



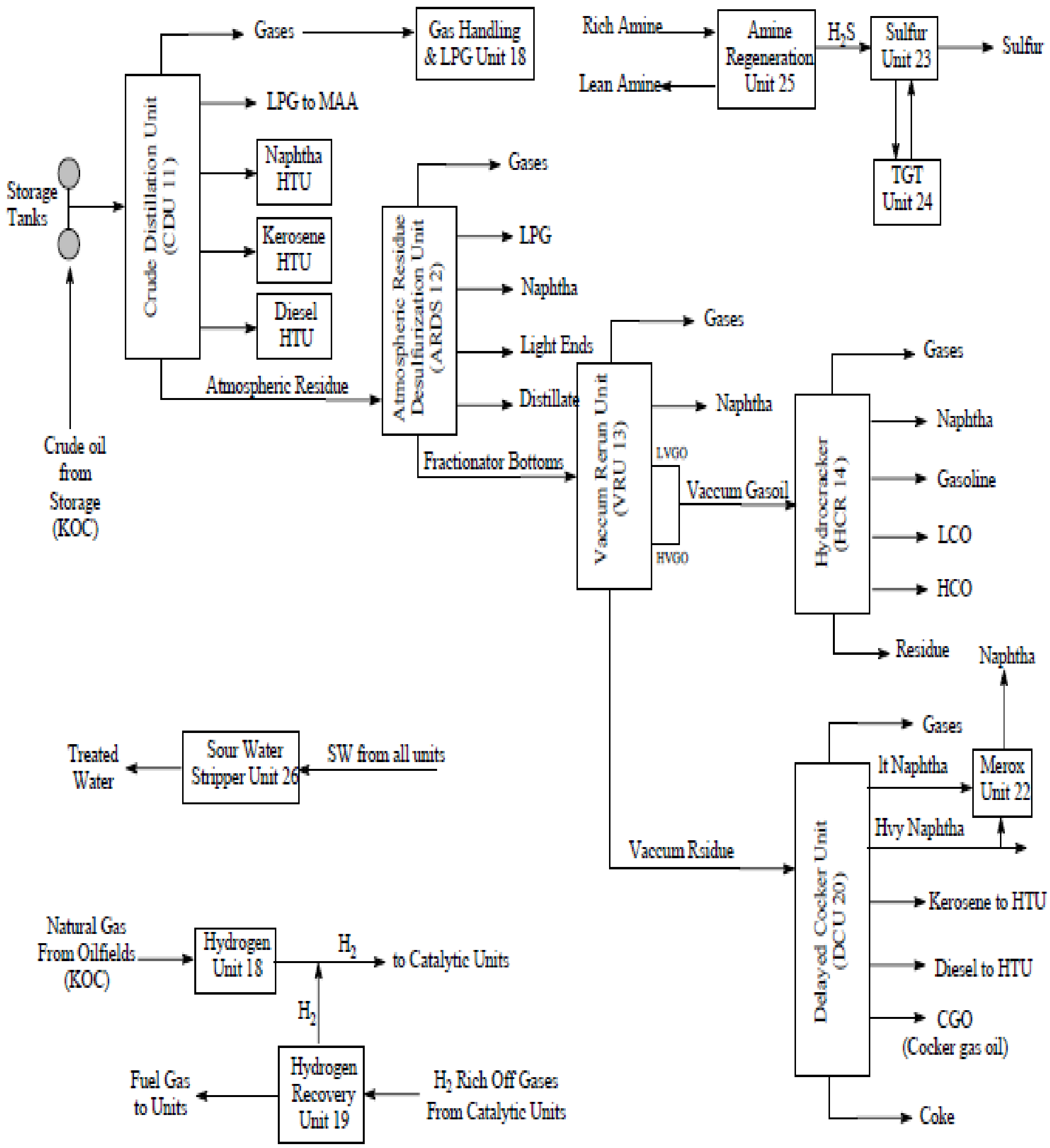
Source: (KNPC, 2020)

Appendix C.3 Shuaiba Refinery layout

Appendix C.4 Shuaiba refinery unit capacities

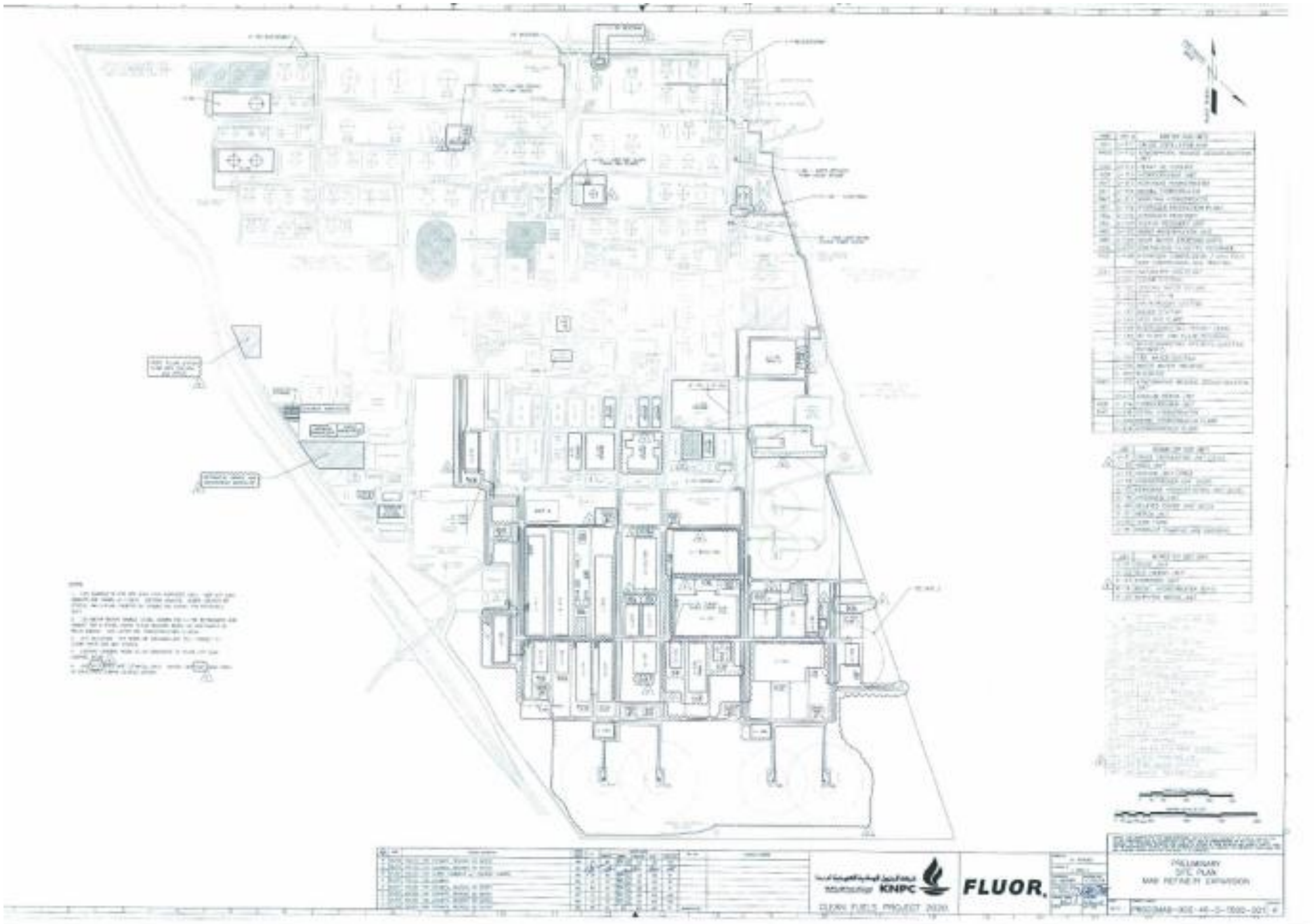
Process Units	No. Of Unit	Design Capacity
Crude Distillation Unit	1	200.000 BPD
Hydrogen Manufacturing Units	3	222 MMSCF/D (H_2 production)
Catalytic Reforming Unit	1	15800 BPD
ISO Cracker Unit	1	46000 BP/D
ISO Max Unit (with recycle)	1	36000 BPD
H- Oil Unit (A & B Trains)	1	54000 BPD
Naphtha Fractionation Unit	1	65000 BP/D
Naphtha Unifining Unit	1	26000 BPD
Kerosene Unifining Unit	1	35000 BPD
Light Diesel Unifining Unit	1	17000 BPD
Heavy Diesel Unifining Unit	1	12000 BPD
Kerosene Merox Unit	1	20000 BPD
Sulfur Recovery Plant	2	600 LT/D (each)
Acid Gas Removal Plant	1	72.2 MMSCFD
Tail Gas Treating Unit	1	69216 NM3/Hr
H-Oil Vacuum Distillation Unit	1	46000 BPD

Source: (KNPC, 2019)



Source: (Alaimi, 2018)

Appendix C.5 Process scheme for MAB Refinery



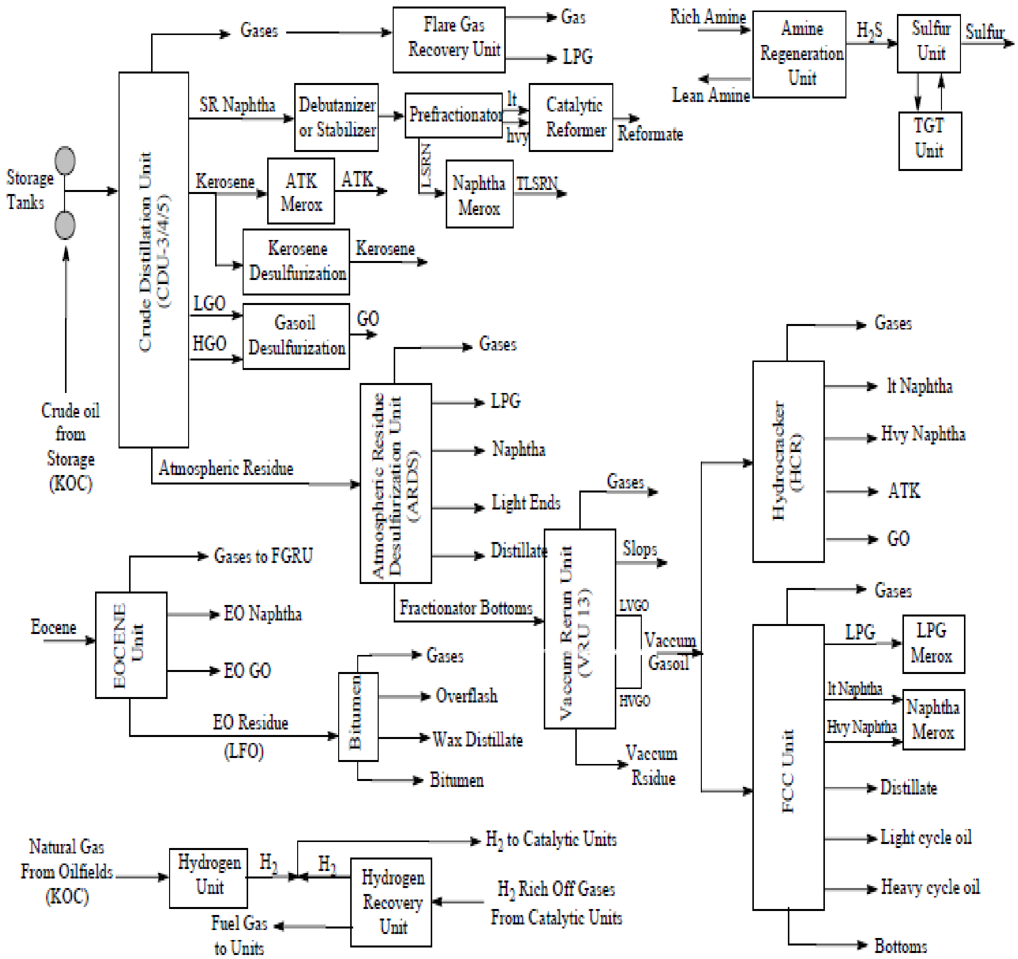
Source: (KNPC, 2020)

Appendic C.6 Mina Abdullah (MAB) Refinery layout

Appendix C.7 Mina Abdullah (MAB) Refinery unit capacities

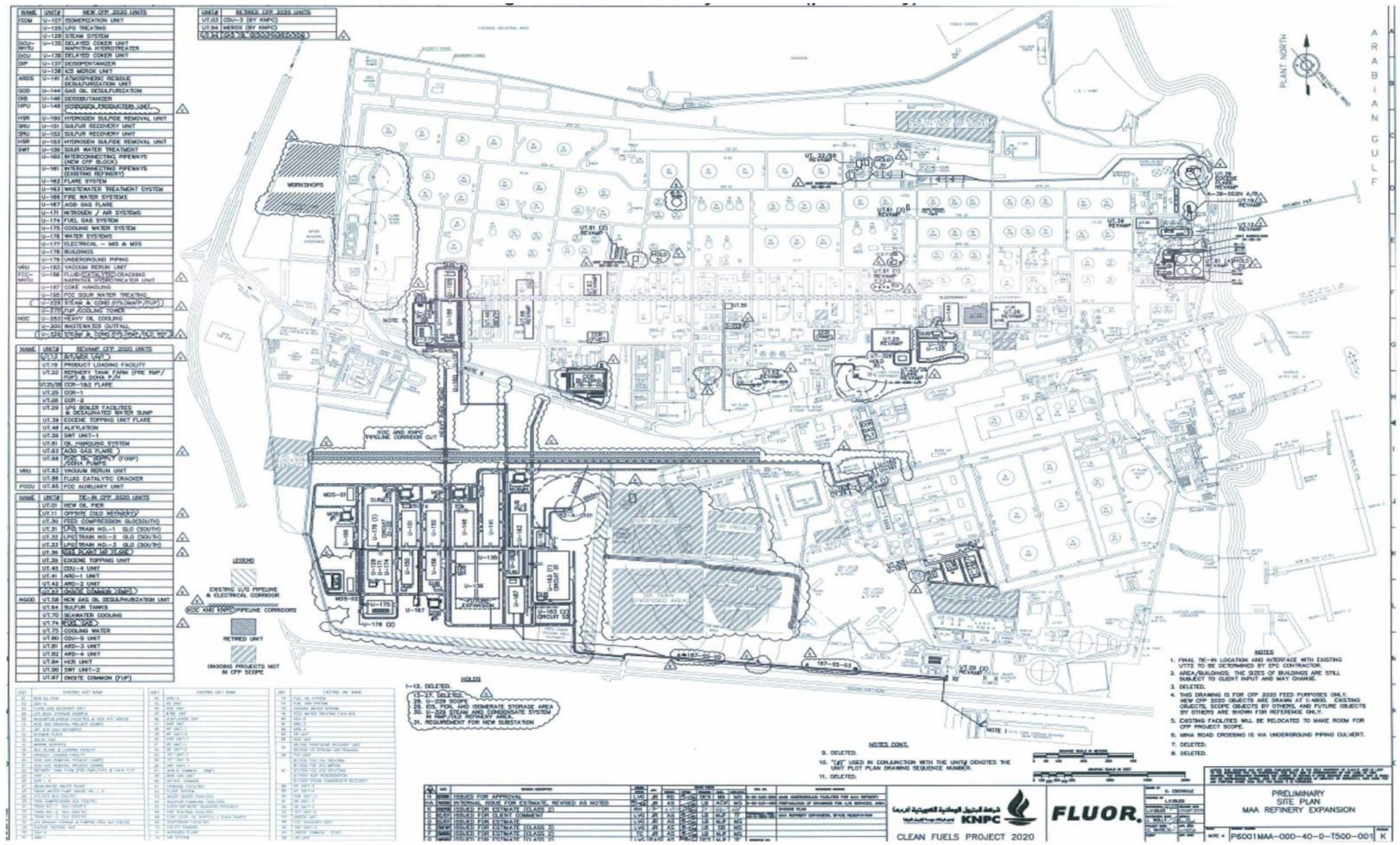
Unit	No. Of Units	Actual Capacity
Crude Distillation Units	3	466,000 bpd
EOCENE Topping Unit	1	24,000 bpd
Bitumen Production Unit (Asphalt)	1	11,000 bpd
Atmospheric Residue Desulfurization Unit (ARDS)	4	132,000 bpd
Naphtha Reforming Units	2	35,000 bpd
Kerosene Desulfurization Units	1	20,000 bpd
Gas oil Desulfurization Units	1	61,600 bpd
Vacuum Distillation Unit	1	85,000 bpd
Hydro Cracking Units (HCR)	1	40,000 bpd
Fluid Catalytic Cracking Unit	1	40,000 bpd
Hydrogen Recovery Unit	1	56,000 MMSCFD
Hydrogen production Units	4	198 MMSCFD
Sulfur Recovery Unit	4	1,334 MTPD
Merox Unit	1	20,000 BPSD
CCR Naphtha Reformers	2	-
Gas Oil Desulfurization Unit	1	61,600 BPSD
New Gas Oil Desulfurization Unit	1	70,000 BPSD
Tail Gas Treatment Unit (TGT)	3	727 MTPD
Sour Water Treating Unit (SWT)	2	1053 GPM

Source: (KNPC, 2019)



Source: (Alaimi, 2018)

Appendix C.8 A Simplified process flow diagram for MAA



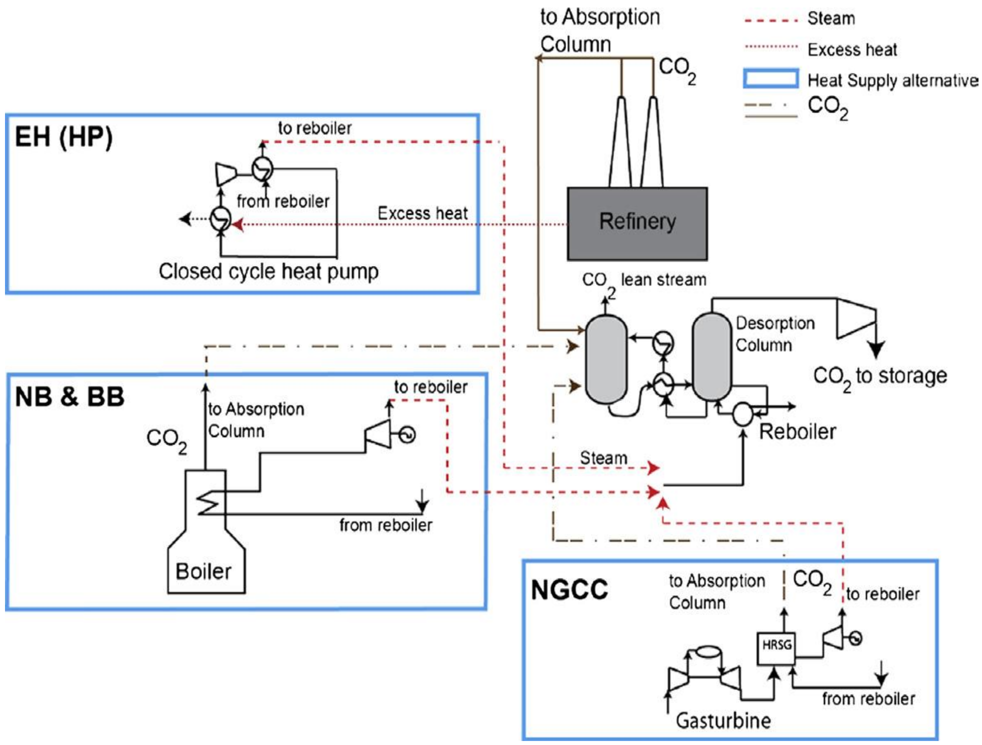
Source: (KNPC, 2020)

Appendix C.9 Mina Al Ahmadi (MAA) Refinery layout

Appendix C.10 Mina Al Ahmadi (MAA) Refinery unit capacities

Unit	No. Of Units	Actual Capacity
Crude Distillation Units	3	466,000 bpd
EOCENE Topping Unit	1	24,000 bpd
Bitumen Production Unit (Asphalt)	1	11,000 bpd
Atmospheric Residue Desulfurization Unit (ARDS)	4	132,000 bpd
Naphtha Reforming Units	2	35,000 bpd
Kerosene Desulfurization Units	1	20,000 bpd
Gas oil Desulfurization Units	1	61,600 bpd
Vacuum Distillation Unit	1	85,000 bpd
Hydro Cracking Units (HCR)	1	40,000 bpd
Fluid Catalytic Cracking Unit	1	40,000 bpd
Hydrogen Recovery Unit	1	56,000 MMSCFD
Hydrogen production Units	4	198 MMSCFD
Sulfur Recovery Unit	4	1,334 MTPD
Merox Unit	1	20,000 BPSD
CCR Naphtha Reformers	2	-
Gas Oil Desulfurization Unit	1	61,600 BPSD
New Gas Oil Desulfurization Unit	1	70,000 BPSD
Tail Gas Treatment Unit (TGT)	3	727 MTPD
Sour Water Treating Unit (SWT)	2	1053 GPM

Source: (KNPC, 2019)



Source: (Al-Salem, 2017)

Appendix C.11 The recommended heat supply for CO_2 capture unit

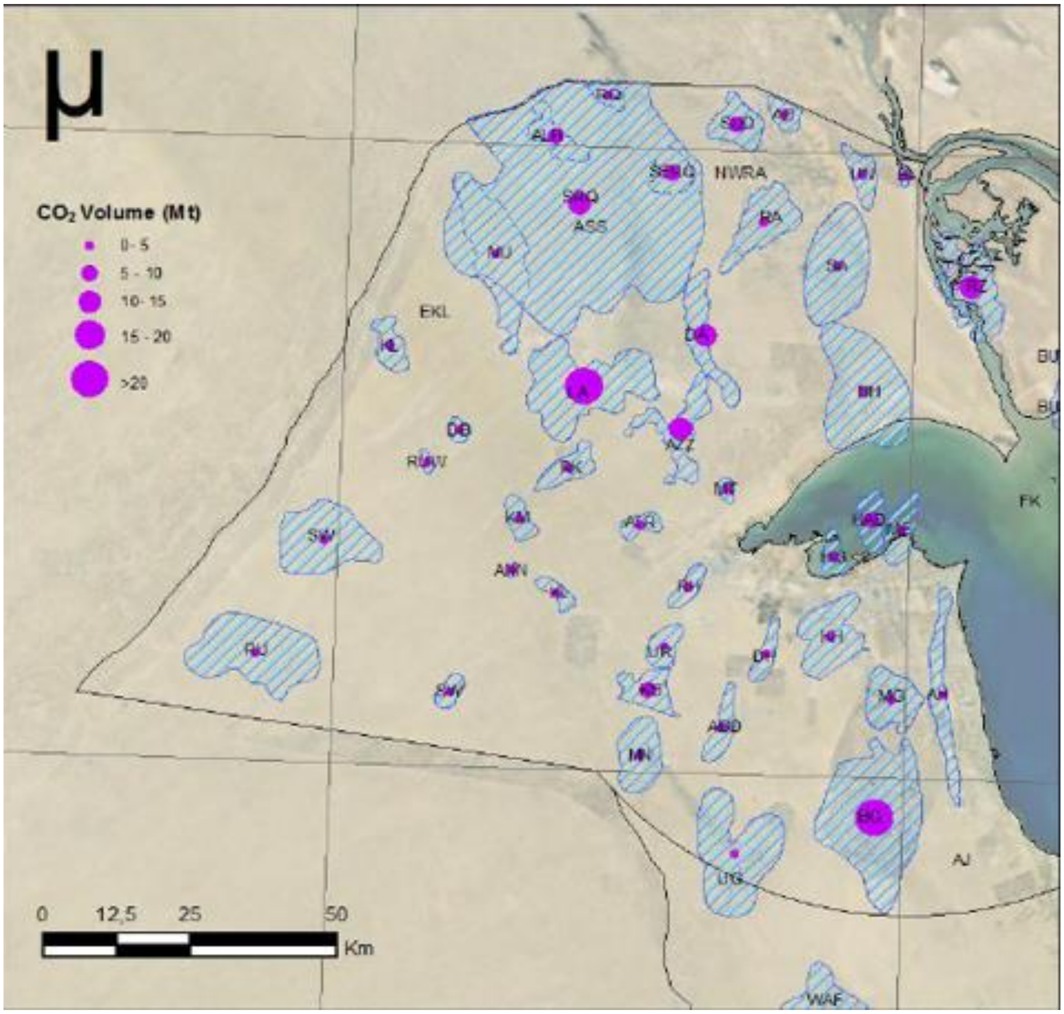
Appendix D. Using CO_2 for Enhanced Oil Recovery (CO_2-EOR) obtained from the discussion group meeting

Appendix D.1 Enhanced Oil Recovery (EOR) screening results

		Reservoir													
		North Kuwait										West Kuwait			
	Process	SA-LB	SA-LB	SA-MA	RQ-LF	RQ-ZU	AD-ZU	RA-LB	RA-LB	RA-MA	RA-ZU	MN-WS	MN-BS	MN-MO	EUG-MO
	Water Flood	PASS	PASS	PASS	PASS	OOND	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	OOND
Chemical Processes	Polymer Flooding	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
	Alkaline/ Polymer Flooding	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
	Surfactant / Polymer Flooding	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
	Alkaline / Surfactant / Polymer Flooding	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
Gas Processes	Carbon Dioxide Miscible	PASS	PASS	PASS	FAIL	PASS	PASS	PASS	OOND	PASS	PASS	OOND	OOND	PASS	OOND
	Hydrocarbon Miscible	PASS	PASS	PASS	FAIL	PASS	PASS	PASS	OOND	PASS	PASS	OOND	OOND	PASS	OOND
	Nitrogen Miscible	FAIL	FAIL	FAIL	FAIL	OOND	OOND	FAIL	FAIL	FAIL	PASS	FAIL	FAIL	PASS	FAIL
	Immiscible Gas	FAIL	PASS	PASS	FAIL	OOND	PASS	PASS	FAIL	PASS	PASS	PASS	FAIL	PASS	OOND
Thermal Processes	Cyclic Steam Stimulation	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
	Steam Flooding	FAIL	FAIL	FAIL	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
	Steam Assisted Gravity Drainage	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
	In Situ Combustion	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	FAIL	FAIL

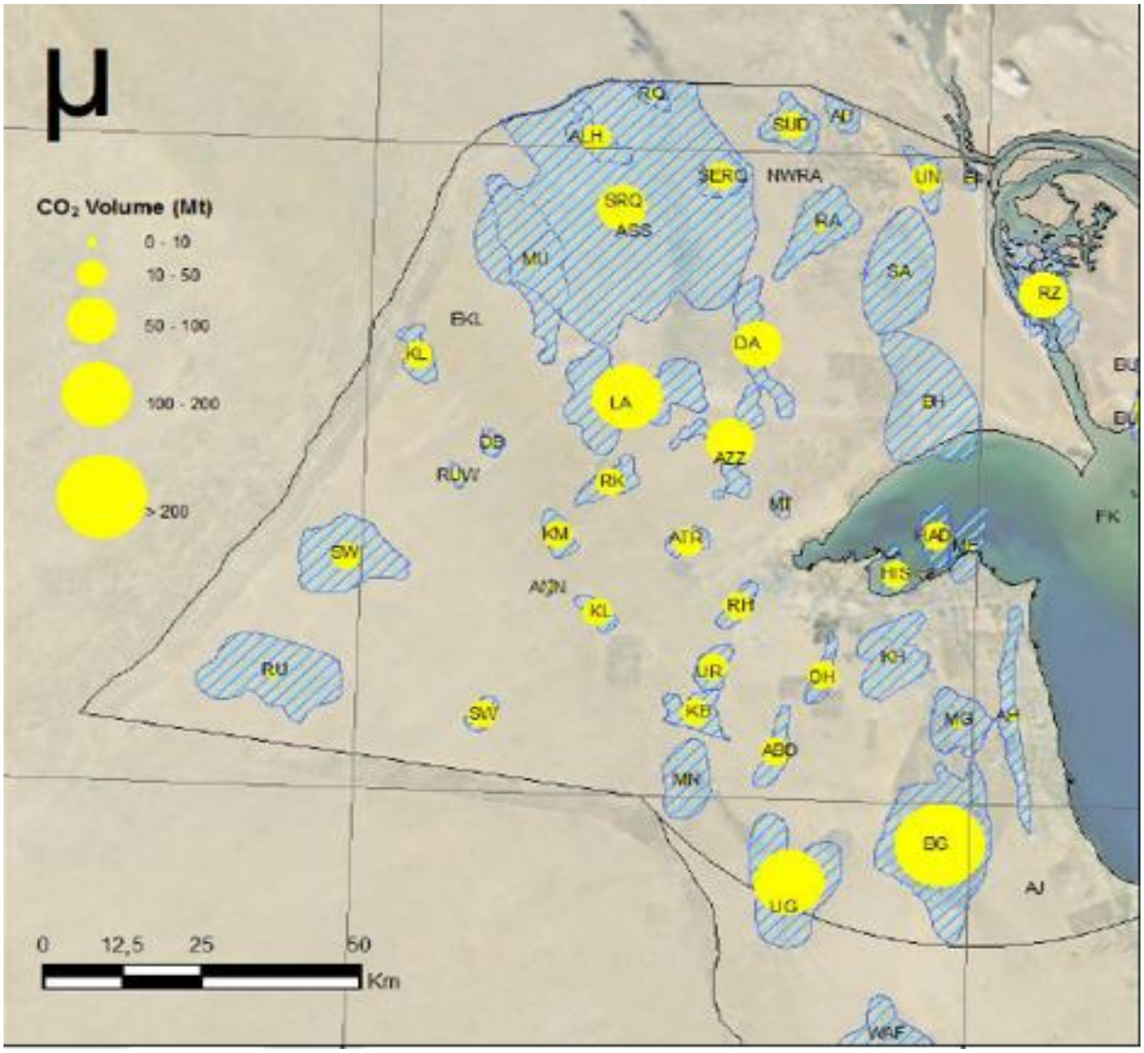
Source: (Sharma, 2017)

Appendix E. Potential sinks obtained from the discussion group meeting



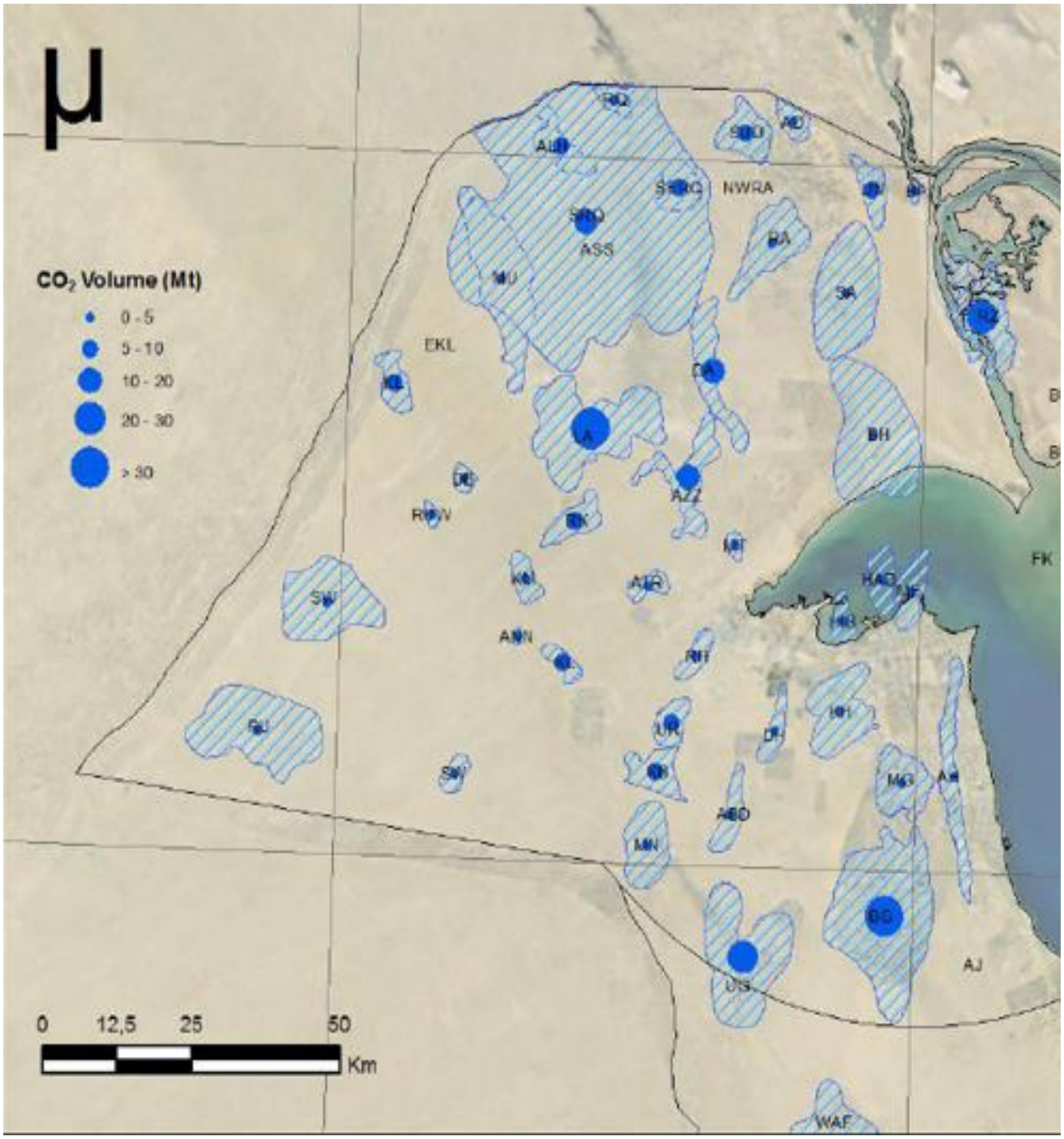
Source: (Sharma, 2017).

Appendix E.1 Map of Kuwait showing the theoretical CO_2 volume storage calculated for Ratawi formation.



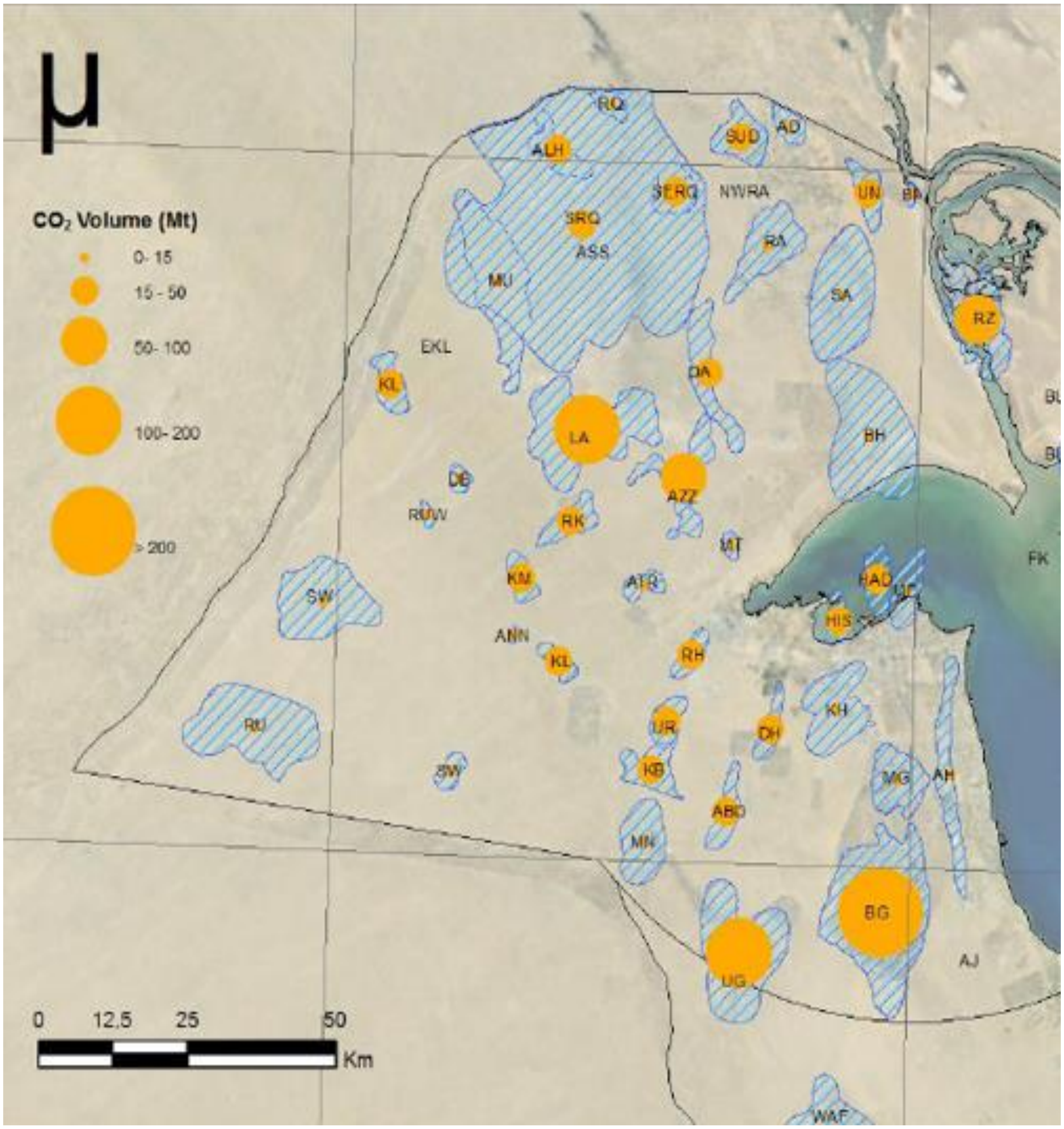
Source: (Sharma, 2017).

Appendix E.2 Map of Kuwait showing the theoretical CO_2 volume storage calculated for Zubair formation.



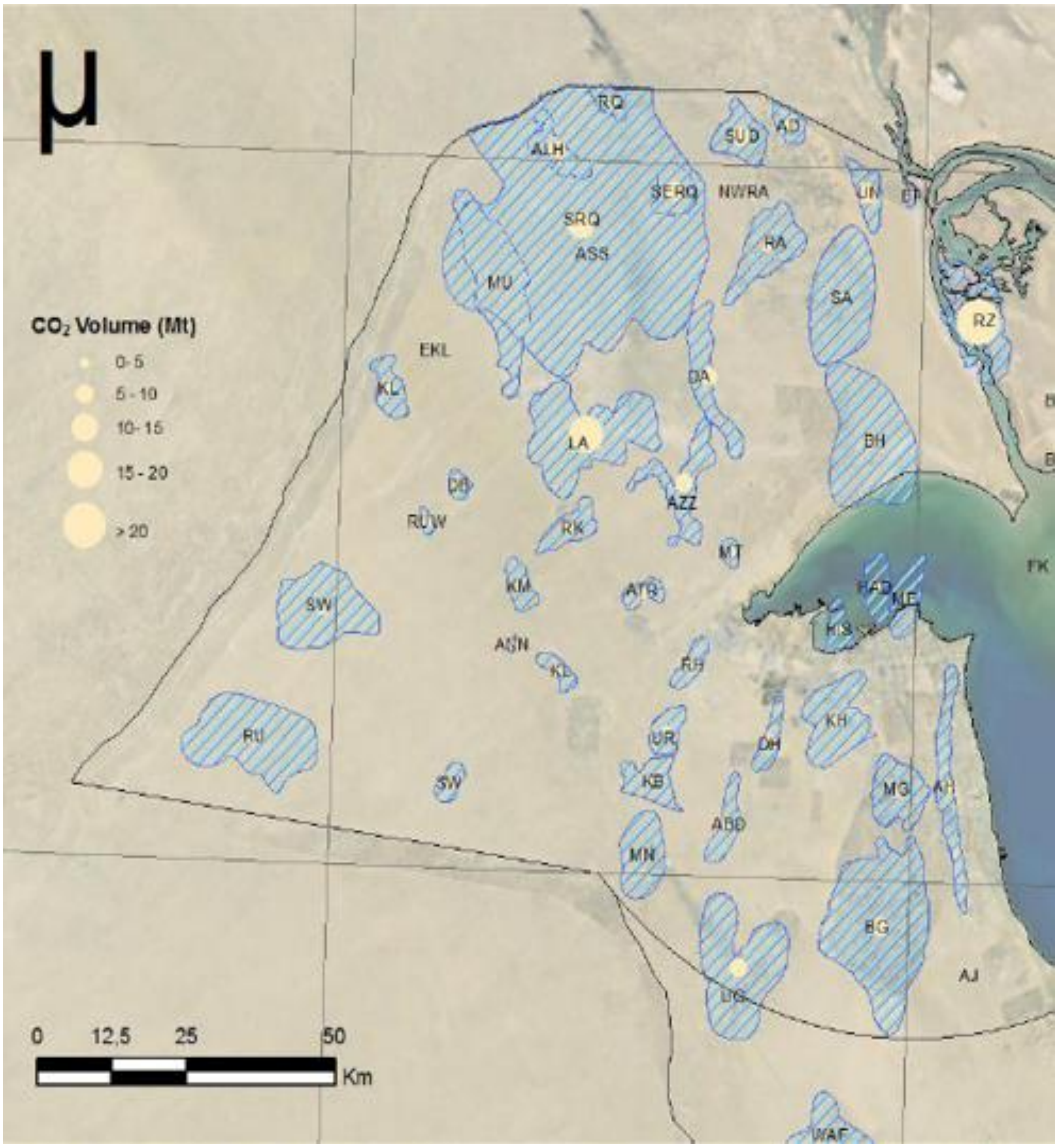
Source: (Sharma, 2017).

Appendix E.3 Map of Kuwait showing the theoretical CO_2 volume storage calculated for the Shuaiba formation.



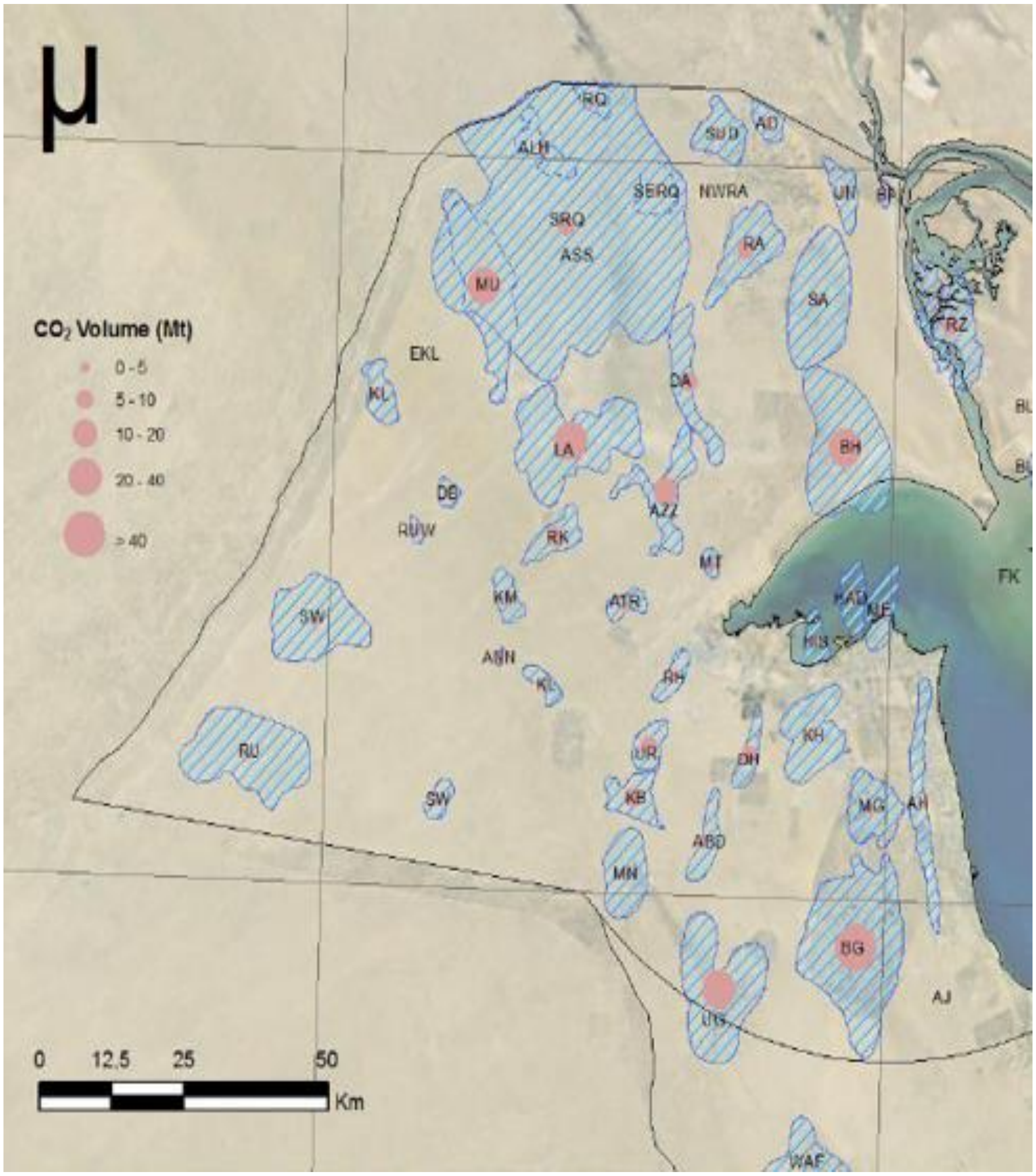
Source: (Sharma, 2017).

Appendix E.4 Map of Kuwait showing the theoretical CO_2 volume storage calculated for the Burgan formation



Source: (Sharma, 2017).

Appendix E.5 Map of Kuwait showing the theoretical CO_2 volume storage calculated for the Mauddud formation



Source: (Sharma, 2017).

Appendix E.6 Map of Kuwait showing the theoretical CO_2 volume storage calculated for the Wara formation

Appendix F. Cement data obtained from the discussion group meeting

Appendix F.1

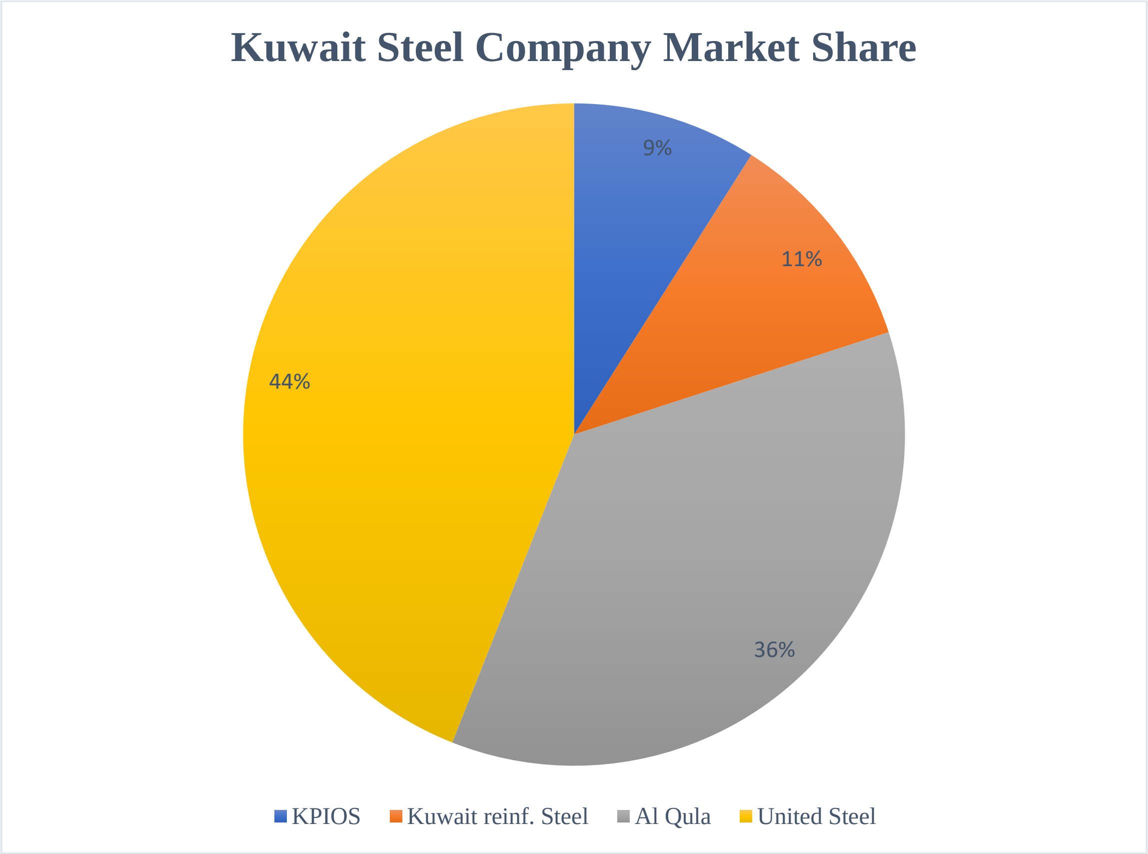
Name	Production of Cement	Import/Export of Cement	Storage and Distribution of Cement	Ready-mix Concrete/Concrete Bricks	Autoclaved Aerated Concrete	Ceramics, Tiles, Pipes	Construction, Contracting, Real Estate
Kuwait Cement	🔵		🔵	🔵			
Hilal Cement		🔵	🔵	🔵			
Kuwait Portland Cement		🔵	🔵	🔵			
ACICO Industries	🔴				🔵		🔴
National Industries				🔴		🔵	🔴
Kuwait Building Materials Manufacturing				🔵			
Kuwaiti British Readymix				🔵			

🔵 Primary activity.

🔴 Secondary activity.

Source: (KMEFIC, 2011)

Appendix G. Steel data obtained from the discussion group meeting



Source: (Gulf Capital Group Limited, 2008)

Appendix G.1 Kuwait steel company market share comparison

Appendix G.2 Steel activity matrix in the state of Kuwait

Company	Upstream	Downstream Products			
	Steel Pellets, Ingots	Semi- finished	Long	Flat	Misc.
United Steel			●		
Al Oula		●			
Kuwait Reinforced Steel			●		
KPIOS				●	
Qudaibi Steel				●	
Hayakel	●				●

Source: (Gulf Capital Group Limited, 2008)

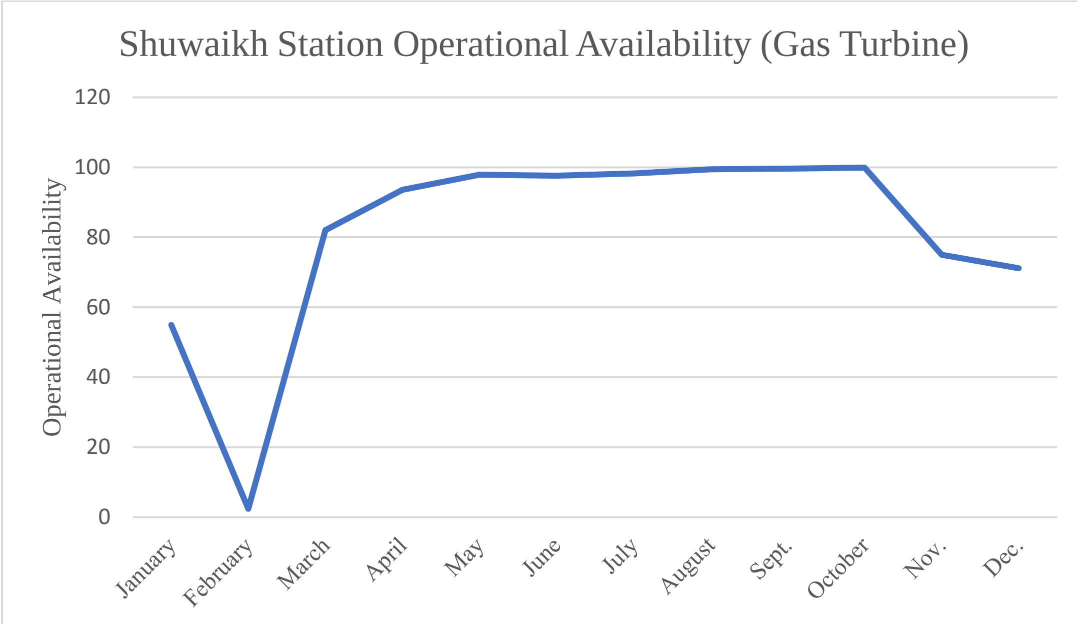
Appendix H. Aluminium data obtained from the discussion group meeting

Appendix H.1 Aluminium production matrix

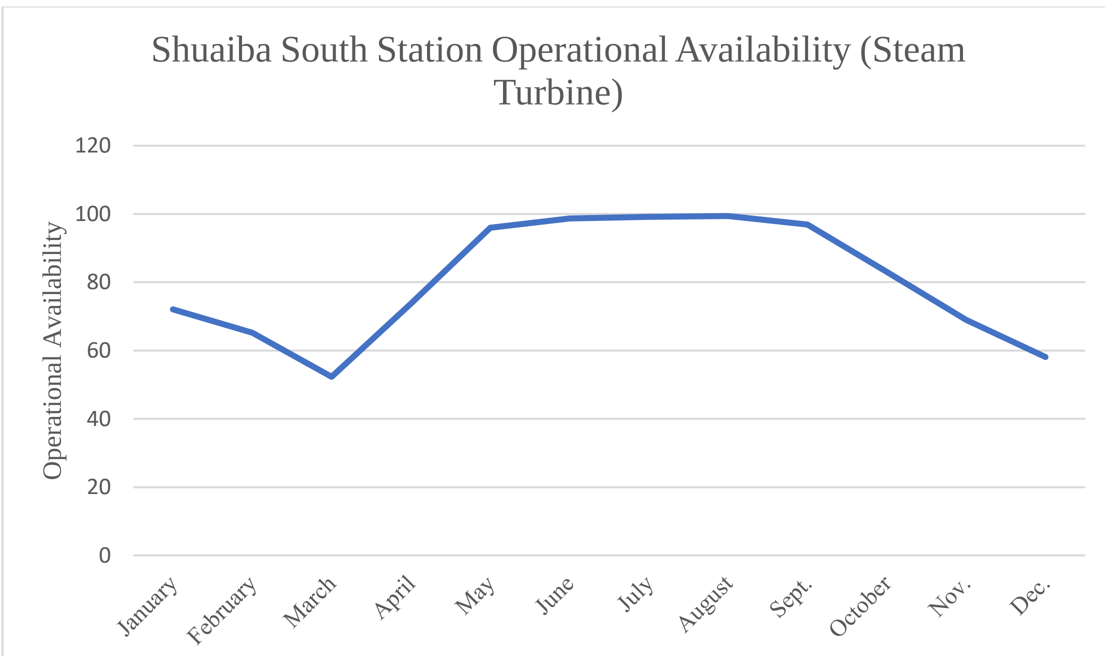
Company	Upstream	Fabricated Metal Products			
	Primary Prod	Extrusions	Façade Syst.	Bev. Cans	Alum. & Glass Misc.
Kalexco		●			●
Al Hadi Aluminium			●		
Aluminium Industries Co.			●		●
Arabian Light Metals		●			●
Kuwait Aluminium Co.			●		●

Source: (Gulf Capital Group Limited, 2008)

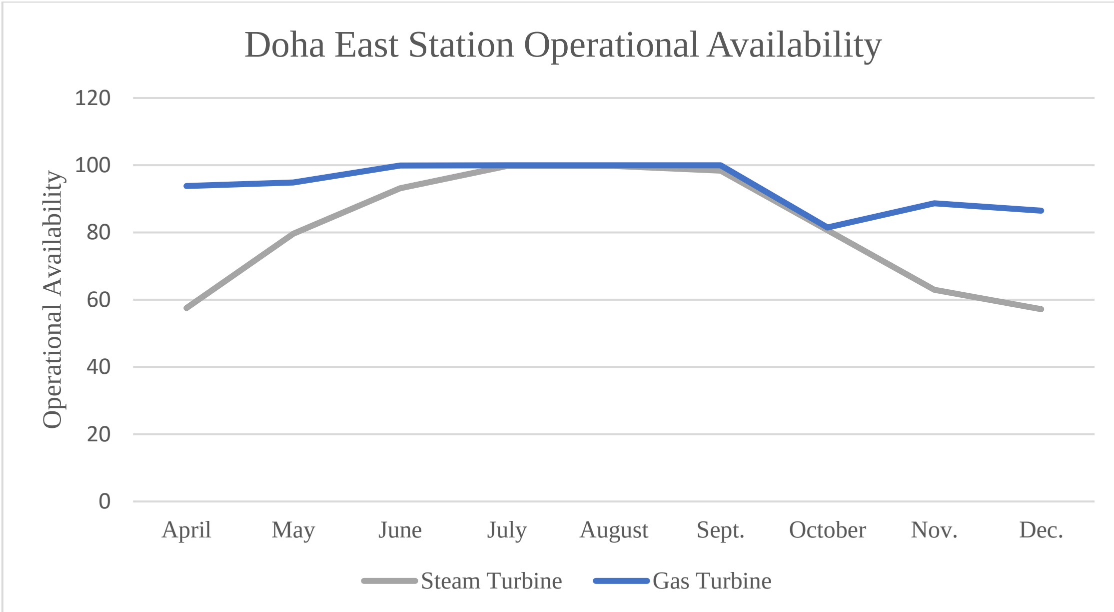
Appendix I. Operation Capacity of Kuwait power plants obtained from the discussion group meeting



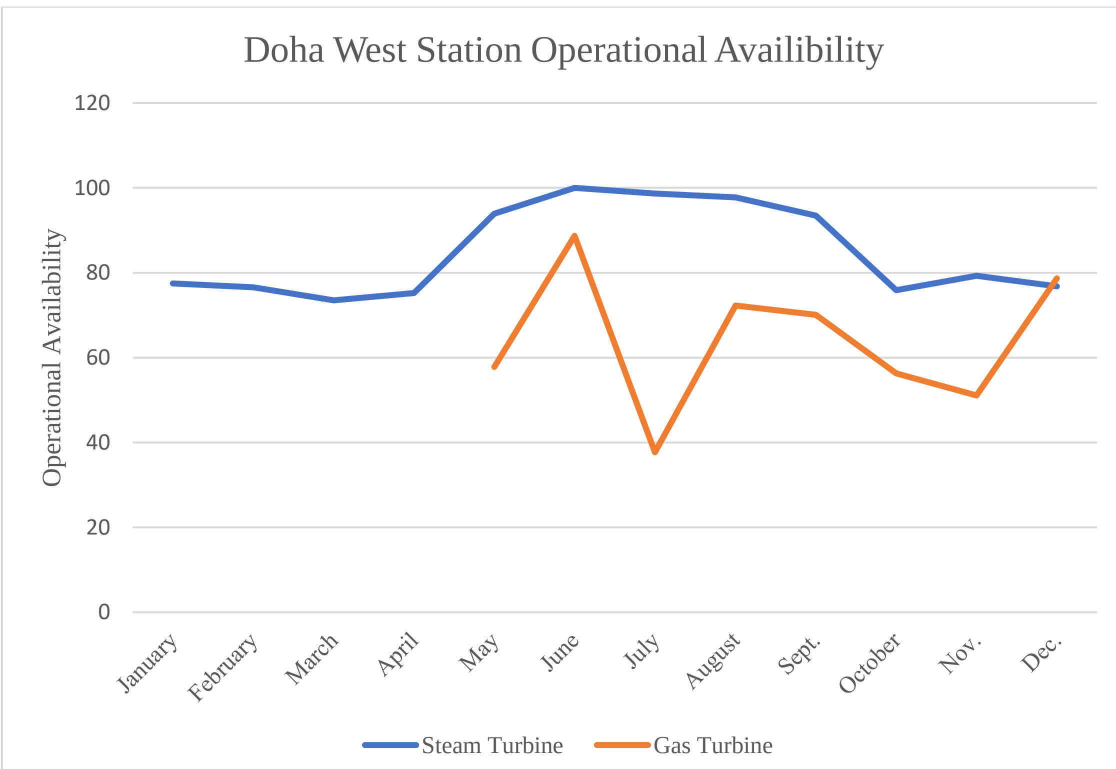
Appendix I.1 Shuwaikh Station Operational Availability (Gas Turbine)



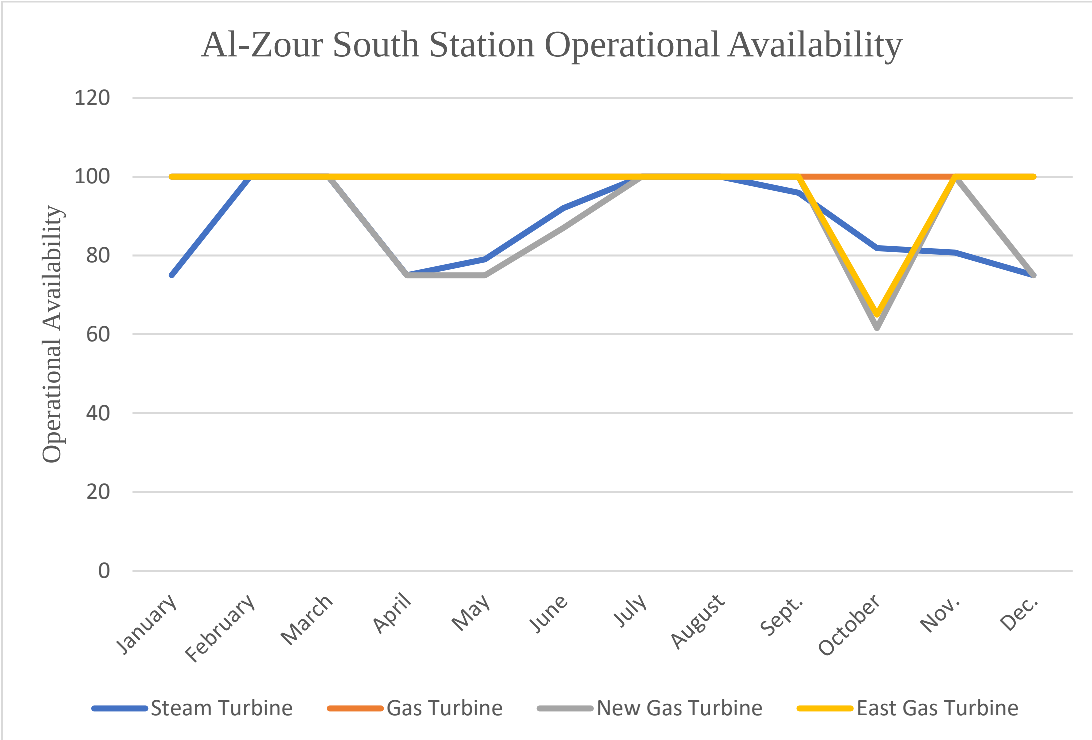
Appendix I.2 Shuaiba South Station Operational Availability (Steam Turbine)



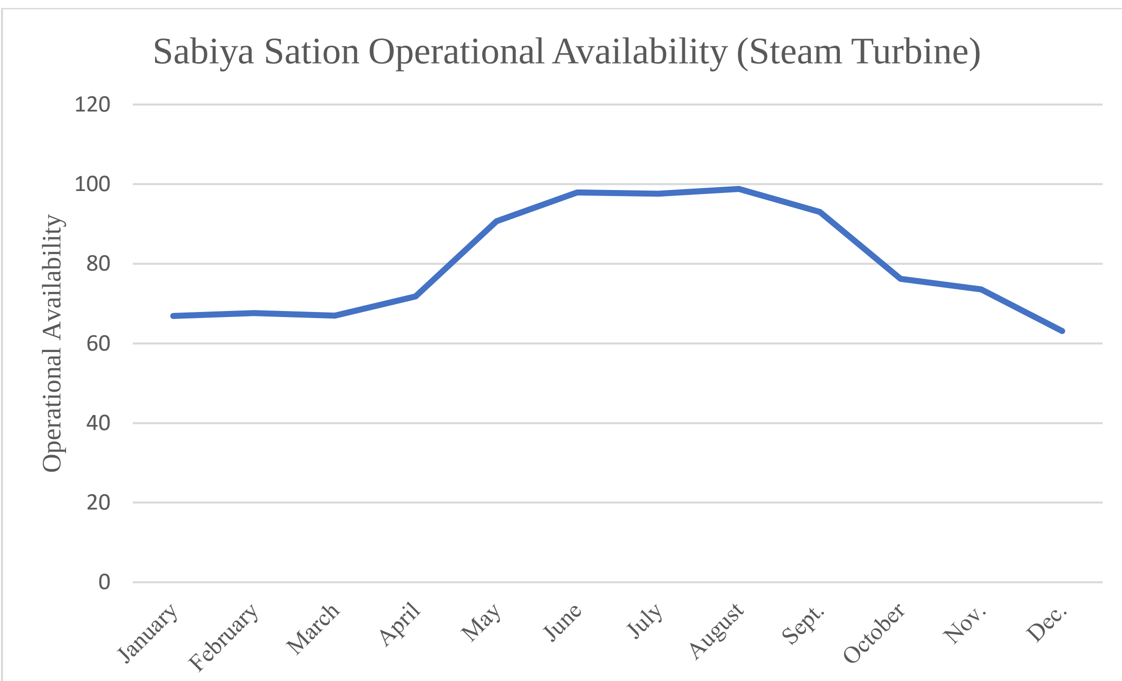
Appendix I.3 Doha East Station Operational Availability



Appendix I.4 Doha West Station Operational Availability



Appendix I.5. Al-Zour south station operational availability



Appendix I.6 Sabiya Station Operational Availability (Steam Turbine)

Appendix J. Simple economic model of capturing CO_2 from five power plants and steam reformers units in the three refineries, obtained from the discussion group meeting

Income:		units
Total CO_2 Emission in Kuwait:	1,650	mmscf/day
	95,700	Ton/Day
	33,973,500	Ton/Year
Income Carbon Credit (20 USD per Ton) per year	679,470,000	USD
One Tone CO_2 Increases Oil Recover	1.25	bbl
Oil production Due to CO_2 Injection	42,466,875	bbl/year
Income per oil sale Oil Price at 65 USD/bbl per year	2,760,346,875	USD
Total Income per year tone of CO_2 capture and EOR	3,439,816,875	USD
Cost		
Cost as per KISR Study at 2000 per mscf	1.2	USD
Cost PerTon	20.69	USD
Cost Per Year	702,900,000	
Net Profit Per year	2,736,916, 875	USD

Source: (Sharma, 2017)

Appendix K. Chemicals

Appendix K.1 Total asphalt (paving) production from Kuwait factories

Name of industrial	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Tarouf Trading Company	Sulaibiya	Asphalt	Kg	232,239,293	327,040,099	340,171,598	299,816,997
Combined Group Contracting Co.	Sulaibiya	Asphalt	Kg	622,884,836	324,859,227	312,594,996	420,113,020
Sayegh and Malloohi Contracting Company	Sulaibiya	Asphalt	Kg	435,448,675	435,448,675	435,448,675	435,448,675
Barco Asphalt Factory	Amghara	Asphalt for Roads	Kg	83,460,996	68,946,040	53,523,900	68,643,645
Massela Asphalt Plant	Sulaibiya	Asphalt	Kg	0	0	38,101,759	12,700,586
Naser Mohammed Al-Sayer Asphalt Production	Amghara	Asphalt	Kg	974,946,904	1,190,163,783	1,260,243,804	1,141,784,830
Bisha for Asphalt Production Company	Sulaibiya	Asphalt	Kg	983,801,934	373,164,093	1,198,883,643	851,949,890
United Gulf for Asphalt Production	Sulaibiya	Asphalt	Kg	138,914,478	123,495,966	112,168,857	124,859,767
Saad Al-Bouss Est. Trading and General Contractings	Sulaibiya	Asphalt	Kg	129,507,879	162,707,212	289,593,327	193,936,139
The Kuwait Company for process Plant Constriction	Sulaibiya	Asphalt	Kg	172,365,101	199,580,643	149,685,482	173,877,075
Medco General Trading and Contracting company	Sulaibiya	Asphalt	Kg	653,173,013	653,173,013	653,173,013	653,173,013
Jalfar Engineering and Contracting Co.	Amghara	Asphalt	Kg	136,077,711	108,862,169	108,862,169	117,934,016
Copri Constriction Enterprises Company	Amghara	Asphalt	Kg	128,224,213	104,660,996	24,719,877	85,868,362
United gulf for asphalt production company	Sulaibiya	Asphalt	Kg	138,914,478	123,495,966	112,168,857	124,859,767.00
Al-Khaled for asphalt factory	Amghara	Asphalt	Kg	87,089,735	783,807,615	68,038,856	312,978,735
Alhajraf asphalt factory	Sulaibiya	Asphalt	Kg	326,586,506	234,144,381	335,658,354	298,796,414
Al-Jahra Asphalt Factory		Asphalt	Kg	79,061,150	81,638,462	82,258,976	80,986,196.00
Combined Group Contracting		Asphalt	Kg	258186495	248440017	73498740	193375084
Total				5,580,883,398	5,543,628,357	5,648,794,883	5,591,102,213

Source: Adapted by the author from (PAI, 2014)

Appendix K.2 Total asphalt (insulation material) production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Industrial Asphalt Emulsion company	Eastern Ahmadi	Asphalt Emulsion	Kg	3,434,000	3,060,000	2,275,000	2,923,000
Poly Urethene Industerial Company		Asphalt Emulsion	Kg	1905088	2422183	3383799	2570356.667
Total				5,339,088	5,482,183	5,658,799	5,493,357

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor for Asphalt is 0.00186 metric ton/kg.

Appendix K.3 Carbon dioxide associated with asphalt production

Carbon dioxide associated with Asphalt production in:	2008	2009	2010
Metric ton	10390373.82	10321345.6	10517283.85
Million metric ton	10.39037382	10.3213456	10.51728385

Appendix K.4 Total paints production from Kuwait factories

Name of industrial Firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Paints Company	Shwaikh	Decoration Paints	Kg	6891903	7581104	9097324	7,856,777.00
		Industrial and Heavy Paints	Kg	1860340	1961602	1992600	1,938,180.67
Hempel Paints (Kuwait)	Shwaikh	Thinner Primer	Kg	1549054	1502749	1546108	1,532,637.00
		High Built and Epoxy Paints	Kg	5861303	6428564	6278397	6,189,421.33
		Other product	kg	314575	227743	171488	237935.3333
International Warba Company for Paints	Sabhan	Industrial Paints	Kg	25680	18020	21660	21786.66667
		Marine Paints	Kg	147060	109730	108650	121813.3333
Seahawk Paints		Sea Dyes	Kg	0	0	9 109.71	3036.57
G.T.C paint Company Limited	Sabhan	Assorted Paints	Kg	13,561,911.52	12,599,550.07	10,921,731	12,361,064.08
Abdul Aziz Abd Almohsen Al-Rashid Sons Factory	Shuaiba	Marble Polish and Primer	Kg	0	444521	489880	311467
		Striper and Coating	Kg	0	390089	417305	269131.3333
International Powder Coating Company	Sabhan	Color Powder	Kg	397347	501673	695811	531610.3333
Al-Matrouk Paints Factory	Shwaikh	Decoration, Artificial and Marine Paints	Kg	687,090	868,840	791,229	782,386
		Other Paints	Kg	51,670	68,245	59,013	59,643
Total				31347933.52	32702430.07	32591195.65	**32,216,889.65**

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor of paint is 0.0054 metric ton/kg.

Appendix K.5 Total carbon dioxide associated with paints production

Total carbon dioxide associated with paints production:	2008	2009	2010
Metric ton	169278.841	176593.1224	175992.4565
Million metric ton	0.169278841	0.176593122	0.175992457

Appendix K.6 Total detergents production from Kuwait factories

Name of industrial Firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Muntaser Shampoo Factory	Sabhan	Hand and utensils liquid soap	Kg	3,538,020	3,175,147	3,401,943	3,371,703.33
		Head cover and Cloak detergent, cloth softer	Kg	1,224,699	1,088,622	1,133,981	1,149,100.67
		Other product	Kg	453592	408233	362874	408233
Al-Sharhan Aerosol Establishment	Shuaiba	Aerosol products	Kg	3,068.75	3,496	4,374.75	3,646.50
		Detergent, Disinfectant, Antisepct	Kg	1,328	1,120.50	1,273.75	1,240.75
Al-Ghanim Detergent and Aerosol Manufacture	Amghra	Dish and Glass cleaner Antiseptic	Kg	14520000	16440000	6060000	12,340,000.00
		Cloth Softener and Bath Cleaner	Kg	2400000	1800000	1740000	1,980,000.00
Subhan Company for the manufacture of Shampoo and creams	Sabhan	Hair shampoo	Kg	997,903	1,360,777	1,360,777	1,239,819.00
		Hair improver	Kg	725748	635029	907,185	755,987
Al-Bahar industries	Sabhan	Detergents and disinfectants	Kg	1,428,816	1,632,933	1,533,142	1,531,630.33
		Adhesive and insulation material and silicon	Kg	996,996	840960	875433	904463
		Car paints	Kg	49895.2	54431.1	54431.1	52919.13333
Al-Sanea chemical products	Sabhan	Detergents and disinfectant chemical	Kg	1,281,852	1,281,852	1,281,852	1,281,852
		Paints and white solvent	Kg	2,866,704	1,959,519	1,469,639	2,098,620.67
		Heating plumes	Kg	181,436,948	181,436,948	181,436,948	181,436,948
Middle East Chemical Manufacturing Company		Car Shampoo,oil remover and superclean	Kg	118,243,600	114,640,600	89,810,600	107,564,933
		Stain Remover	Kg	209,300	324,575	411,700	315,192
		Other products	Kg	257,225	302,100	221,125	260,150
Total				330,635,695	327,386,343	292,067,279	**316,696,438.72**

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor of detergents is 0.00175 metric ton/kg.

Appendix K.7 Total carbon dioxide associated with detergents production

Total carbon dioxide associated with detergents production in:	2008	2009	2010
Metric ton	578612.4662	572926.0996	511117.7376
Million metric ton	0.578612466	0.5729261	0.511117738

Appendix K.8 Total lubricant oil production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait national lubricating oil company	Shuaiba	Automatic engine oils	Kg	2100000	1350000	1400000	1,616,666.67
		Industrial oils	Kg	2200000	1400000	1500000	1,700,000.00
		Engine oils	Kg	1465000	886000	962000	1,104,333.33
Kuwait lubricant oil company	Shuaiba	Greases and lubricants	Kg	19,402,867	14,762,617	12,585,374	15,583,619
		Water	Kg	3,257,700	2,694,339	1,680,106	2,544,048.33
Kuwait Dana for oil company	Shuaiba	Lubricant oils	Kg	44,497,411	44,497,411	44,497,411	44,497,411
		grease	Kg	5443.11	5443.11	5443.11	5443.11
Total				72928421.11	65595810.11	62630334.11	**67,051,521.78**

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor for lubricant oil is 0.00107.

Appendix K.9 Total carbon dioxide from lubricant oil production

Total carbon dioxide from lubricant oil production in:	2008	2009	2010
Metric ton	78033.41059	70187.51682	67014.4575
Million metric ton	0.078033411	0.070187517	0.067014457

Appendix K.10 Total perfume production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Perfumes Factory	Sabhan	Herbal, Palm, Rose and Flower water	Kg	84368.2	76203.5	78925.1	79832.26667
		Cologne Water, Eau De toilette and Perfumes	Kg	406419	393718	397347	399161.3333
		Scented Towels and medical alcohol wipes	Kg	7257.48	7257.48	9071.85	7862.27
Al-Shaya Perfumes Factory	Sabhan	Cologne and Rose, Flower and Plam water	Kg	367499.5	388305	239391.5	331732
Al-Mubrouk Perfumes	Shuaiba	Oud Oil and Mammol	Kg	28000	25000	22000	25000
		Oriental Mixtures, French and Arabian perfumes	Kg	51000	66000	55500	57500
Tabahly Factory for perfumes	Shuaiba	Perfumes and Incense	Kg	0	0	17000	5666.666667
		Mixture	Kg	0	0	34	11.33333333
Azura Perfumes Factory	Western Shuaiba	Cologne Water	Kg	26308.4	26308.4	31751.5	28122.76667
		Perfumes	Kg	26308.4	26308.4	31751.5	28122.76667
Total				997160.98	1009100.78	882772.45	**963011.4033**

Source: Adapted by the author from (PAI, 2014)

Appendix K.11 Total inorganic acid production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Chemkuwait for chemical industries	Shuaiba	Concentrated and diluted sulphuric acid	Kg	52,303,736	44,402,157	44,444,795	47,050,229
		Distilled water	Kg	0	26846.31	70399.82	32415.37667
Total				52,303,736	44,429,003	44,515,195	**47,082,644.71**

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor for sulphuric acid is 0.00014 metric ton/kg.

Appendix K.12 Total carbon dioxide emissions from sulphuric acid

Total carbon dioxide emission from sulphuric acid in:	2008	2009	2010
Metric ton	7322.52304	6216.30198	6222.2713
Million metric ton	0.007322523	0.006216302	0.006222271

Appendix K.13 Total fertilizer production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Petrochemical industries company	Shuaiba	Urea	Kg	662,716,596	799,111,822	926,056,904	795,961,774.03
		Amonia	Kg	444,801,750	520,007,365	576,851,561	513,886,892.00
Total				1,107,518,346	1,319,119,187	1,502,908,465	**1,309,848,666**

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor of nitrogen fertilizer is 0.00462 metric ton/kg.

Appendix K.14 Carbon dioxide emissions from nitrogen fertilizers

Carbon dioxide emission from nitrogen fertilizers in:	2008	2009	2010
Metric ton	5116734.759	6094330.644	6943437.109
Million metric ton	5.116734759	6.094330644	6.943437109

Appendix K.15 Total pharmaceutical industries production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Saudi pharmaceutical industries	Sabhan	Injection bottles	Kg	2,347	2,522	3,875	2,915
		Pills and capsules	Kg	245.59	349.874	180.342	258.602
		Syrup	Kg	1214.75	1,792.65	1,688	1,565
Total				3,807	4,665	5,743	**4,738**

Source: Adapted by the author from (PAI, 2014)

Appendix K.16 Total glue production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
G.T.C. adhesives factory	Sabhan	Assorted adhesive materials, thermoplastic and foam tchechol compound	Kg	17933981.55	17176864.61	14024905.63	16378583.93

Source: Adapted by the author from (PAI, 2014)

Appendix K.17 Total sponge production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Baghi United for Sponge Industries	Sabhan	Synthetic sponge and polyester products	Kg	0	0	1,756,310	585,437
		Spring mattresses and bed sheets	Kg	0	0	631,218.40	210,406.13
Abbas Ali Al-Hazeem and Partners	Sabhan	Spring mattresses	Kg	666,780	666,780	889040	740866.6667
		Divan beds and saloons	Kg	361174.1	361174.1	361174.1	361174.1
		Sponge and its derivatives	Kg	122,500	122,500	122,500	122,500
Kuwait sponge industries company	Shwaikh	Artificial sponge	Kg	84720	84516	86186	85,140.67
Al-Eyash sponge and polyester factory	Amghrah	Polyester	Kg	362874	408233	453592	408233
		Coverlets and bed sheets	Kg	370,000	420,000	470,000	420,000
		Pillows and mattresses	Kg	2,449,399	2,806,603	3,504,001	2,920,000.88
United oil project company		Alkid	Kg	1340744.657	980329.2312	970078.0437	1097050.644
		Polyester	Kg	611263.7994	437303.868	408470.8154	485679.4943
Kuwait mattress company		Mattresses	Kg	1340227.8	1319335.36	1313556.6	1,324,373.25
National sponge factory and bed health	Shuaiba	Sponge sheet	Kg	35600	38600	42500	38900
		Sponge mattresses	Kg	8,178,800	8,579,236	9,023,756	8,593,931
Al-jerawy sponge industriea	Al-Rai	Artificial sponge	Kg	1,859,729	1,859,729	1,905,088	1,874,848.67
		Sponge mattresses and pillows	Kg	3,111,640	3,022,736	3,156,092	3,096,822.67
Al-Farres industries	Sabhan	Mattresses and head board	Kg	42407.208	37072.968	84236.54	54572.23867
		Divan and seat sets	Kg	30220.69	17690.16	3,685.45	17,198.77
		Other miscellaneous	Kg	54061	13636	36883	34860
National sponge factory and bed health	Shuaiba	Sponge sheet	Kg	35600	38600	42500	38900
		Sponge Mattresses	Kg	8,179,168	8,579,236	9,023,756	8,594,053.33
Total				29236909.05	29793310.48	34,284,624	**31,104,947.85**

Source: Adapted by the author from (PAI, 2014)

Appendix K.18 Total catalyst production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait catalyst company	Shuaiba	Catalysts	Kg	5,539,000	3,051,000	562000	3,050,666.67
National chemical and prtroluem industry	Shuaiba	Oil demulsifier	Kg	4,300,000	4,500,000	4,700,000	4,500,000
		Scale inhibitor	Kg	1,960,000	1,700,000	2,000,000	1,886,666.67
		Corrosion and foam inhibitor	Kg	2,180,000	3,573,000	2,280,000	2,677,666.67
		Other product	Kg	360000	0	350000	236666.6667
Total				14,339,000	12,824,000	9892000	**12,351,666.67**

Source: Adapted by the author from (PAI, 2014)

Appendix K.19 Total plastic (primary form) production from Kuwait factories

Type of industry	Name of industrial firm	Location	Product type	Unit	Production			
					2008	2009	2010	Average
Plastic in primary forms	Sulaiman Alqudaibi Co. for G.R.P and Plastic Product	Sabhan	GRP Pipes	Kg	13,333,320	13,333,320	13,333,320	13,333,320.00
			Jacking Pipe	Kg	119,988	119,988	119,988	119,988
			Manholes and Other Product	Kg	134,985	134,985	134,985	134,985
	Al-Sanea for Plastic Pipes and Fitting Factory	Sabhan	Plastic	Kg	1,315,418	952,544	907,185	1,058,382.33
			Plastic junction	Kg	616886	401883	362874	460547.6667
	Al-Ahlea Circle Plastic Production Factory		Plastic Reinforced Fiberglass	Kg	238590	301185	347452	295742.3333
	Dawood Al-Farhan for Irregular Pipes Production		Plastic Irregation pipes	Kg	875000	1125000	875000	958,333.33
Total					16,634,187	16,368,905	16,080,804	16,361,298.67

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor of plastic is 0.0027 metric ton/kg.

Appendix K.20 Total plastic production in primer form (without GRP pipes)

Total carbon dioxide emission from total plastic production in primer form (without GRP pipes)	2008	2009	2010
Metric ton	8912.3409	8196.0795	7418.2068
Million metric ton	0.008912341	0.00819608	0.007418207

Notes:

Emission Factor of G.R.P pipes is 0.0081 metric ton/kg.

Appendix K.21 Total carbon dioxide from G.R.P pipes

Total carbon dioxide from G.R.P pipes	2008	2009	2010
Metric ton	107999.892	107999.892	107999.892
Million metric ton	0.107999892	0.107999892	0.107999892

Appendix K.22 Total plastic (boats) production from Kuwait factories

Type of industry	Name of industrial firm	Location	Product type	Unit	Production			
					2008	2009	2010	Average
Building and reparing boat	United Fiberglass Factory	Amghara	Fiberglass and Polyethylene Tanks	Kg	200000	182,500.00	172,500.00	185,000.00
			Fiberglass Plant Pots and Pipes	Kg	73.3	57.87	46.295	59.155
			Boat Decoration	Kg	3,800	3,200	3,400	3,467
	Al-Rodan fiberglass factory		Multiple size boat	Kg	18,250	6,000	9,500	11,250
	Seahawk boat		Multiple size boat	Kg	0	0	5,250	1,750
Total					222123.3	191,757.87	190,696.30	201,525.82

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor of plastic is 0.0027 metric ton/kg.

Appendix K.23 Total carbon dioxide emissions from production of plastic used in building boats

Total carbon dioxide emission from production of plastic used in building boats	2008	2009	2010
Metric ton	599.73291	517.746249	514.8799965
Million metric ton	0.000599733	0.000517746	0.00051488

Appendix K.24 Total plastic (shoes) production from Kuwait factories

Type of industry	Name of industrial firm	Location	Product type	Unit	Production			
					2008	2009	2010	Average
Shoes and snadals	Kuwait Company for plastic product	Sabhan	Plastic Bags and Rolls	Kg	102512	97068.8	95254.4	98278.4
			Houses and Rigid Pipes	Kg	122470	108862	108862	113398
Total					224982	205930.8	204116.4	211676.4

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor of plastic is 0.0027 metric ton/kg.

Appendix K.25 Total carbon dioxide emissions from shoes and sandals

Total carbon dioxide emission from shoes and sanadals in	2008	2009	2010
Metric ton	607.4514	556.01316	551.11428
Million metric ton	0.000607451	0.000556013	0.000551114

Appendix K.26. Total plastic (Curtly) production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2010	2009	2008	Average
Kuwait Tower Nilon Factory	Sabhan	Plastic Bags and Rolls high and low Density	Kg	2,564,611	2,394,968	2,563,704	2,507,761.00
Bubyan for the packaging industry	Amghara	Foam and plastic packs	Kg	616886	589670	571526	592694
Green Plastic Factory (Plastic Bags Manufacture)	Shuaiba Western industrialized	Plastic Bags and Rolls	Kg	1063221	1057777	495323	872107
European Plastic	Subhan	Plastic Bags	Kg	94347.2	87089.7	64410.1	81949
Al-Arabi Plastic Factory	Sabhan	High Density Bags	Kg	3,220,506	2,726,090	2,449,399	2,798,665
		Low Density Bags	Kg	2,431,255	2,426,719	2,295,177	1,272,326.50
		Cellophane Bags	Kg	172365	172365	136078	160269.3333
The plastic company Ltd.	Sabhan	Boxes and household Utenils	Kg	496,267	199,852.50	658,934	451,684.50
		Food Boxes and cups	Kg	18,709	16,183	17,049	17,313
		Other product	Kg	57,669	50,586	57,839	55,365
Packaging and plastic industries Company	Shuaiba	Polyethylene and Polypropylene	Kg	7,076,041	6,304,934	6,259,575	6,546,850.00

Source: Adapted by the author from (PAI, 2014)

Appendix K.27 Total plastic (Curtly) production from Kuwait factories

Name of industrial firm	Location	Product type	Unit	Production			
				2010	2009	2008	Average
Qaroh P.E.T Products Company	Shuaiba	Plastic Rolls	Kg	70516	100596	122811	97974.33333
		Bottles and Bottles Caps	Kg	858.25	3,076.75	8,148	4027.666667
		Pet Perform and Pharmaceutical Bottle	Kg	2907.14	28042.9	2395.8	19836.7
Shorouq Pack Soft	Sabhan	Packing and Packaging Materials	Kg	1,270,059	1,224,699	1,224,699	1,239,819.00
		Plastic Stickers	Kg	1,800	1,400	1,300	1,500
Al-Khalid plastic Industries Company	Amghara	Plastic Bags	Kg	1,360,777	1,360,777	1,088,622	1,270,058.67
Genoa Plastic Industries	Amghara	PET preform	Kg	5,964,740	1,123,095	0	2,362,611.67
Total				36,660,406	33,114,632	23,727,717	30,759,921.30

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor of plastic is 0.0027 metric ton/kg.

Appendix K.28 Total carbon dioxide emissions from total plastic produce in curtly

Total carbon dioxide emission from total plastic produce in curtly in	2008	2009	2010
Metric ton	64064.83563	89409.50735	98983.0959
Million metric ton	0.064064836	0.089409507	0.098983096

Appendix K.29 Total industrial gases production from Kuwait factories

Name of industrial Firm	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Oxygen Company	Shuaiba	Oxygen Gas and liquid Oxygen	Kg	102,149,002	367,409,820	386,460,699	285,339,840.33
		Nitrogen Gas and liquid Nitrogen	Kg	77,564,295	149,685,482	144,242,374	123,830,717
		Liquid Argon	Kg	7,076,041	14,514,956	15,422,141	12,337,713
Refrigeration and oxygen company Ltd	Shwaikh	Oxygen and Argon	Kg	2252835452	1937862724	2073403382	2,088,033,852.67
		Nitrogen and hydrogen	Kg	9520082844	6904378032	9050444190	8,491,635,022.03
Kuwait Oxygen Company	Shuaiba	CO_2	Kg	518002	539775	800137	619304.6667
		Nitrous Oxide and Acetylene	Kg	235868	253105	250383	246452
Kuwait Industrial gases corporation	Shuaiba	Liquid oxygen, Nitrogen, Argon	Kg	60,012,085	51,833,814	60,653,465	57,499,788.00
		Oxygen and nitrogen gases	Kg	85,434,123	69,845,060	80,544,397	78,607,860.00
Kuwait oil tanker company-Bottling paint gas cylinder	Shuaiba	Liquefied gas cylinder	Kg	142509216	141955596	138704112	141,056,308.00
Total				12,248,416,928	9,638,278,364	11,950,925,280	**11,279,206,857.37**

Source: Adapted by the author from (PAI, 2014)

Appendix K.30 Total oxygen production from Kuwait factories

Oxygen produces from in (Kg)	2008	2009	2010
Kuwait Oxygen Company	102,149,002	367,409,820	386,460,699
Refrigeration and oxygen company Ltd	1,126,417,726.00	968,931,362.00	1,036,701,691.00
Kuwait Industrial gases corporation	42,717,061.50	34,922,530.00	40,272,198.50
Total	1,271,283,789.5	1,371,263,712.00	1,463,434,588.5

Notes:

Emission Factor of oxygen is 0.00041 metric ton/kg.

Appendix K.31 Total carbon dioxide associated with oxygen production

Total carbon dioxide associated with oxygen production in	2008	2009	2010
Metric ton	521,226.35	562,218.12	600,008.18
Million metric ton	0.521226354	0.562218122	0.600008181

Appendix K. 32 Total nitrogen production from Kuwait factories

Total nitrogen produces (Kg):	2008	2009	2010
Kuwait oxygen company	77,564,295	149,685,482	144,242,374
Refrigeration and oxygen company Ltd	4760041422	3452189016	4525222095
Kuwait Industrial gases corporation	62721089.83	52200468	60490020.17
Total	4,900,326,807	3,654,074,966	4,729,954,489

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor of nitrogen is 0.00043 metric ton/kg.

Appendix K. 33 Total carbon dioxide associated with nitrogen production

Total carbon dioxide associated with nitrogen production in:	2008	2009	2010
Metric ton	2107140.527	1571252.235	2033880.43
Million metric ton	2.107140527	1.571252235	2.03388043

Appendix K.34 Total carbon dioxide production from Kuwait factories

Total carbon dioxide produces from Kuwait Oxygen Company	2008	2009	2010
Kg	518002	539775	800137

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor of carbon dioxide is 0.00082 metric ton/kg.

Appendix K.35 Total carbon dioxide emissions from carbon dioxide production

Total carbon dioxide emission from carbon dioxide production	2008	2009	2010
Metric ton	424.76164	442.6155	656.11234
Million metric ton	0.000424762	0.000442616	0.000656112

Appendix K.36 Total hydrogen production from Kuwait factories

Total hydrogen produces from Refrigeration and oxygen company Ltd in:	2008	2009	2010
Kg	4760041422	3452189016	4525222095

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission Factor for hydrogen is 0.00163 metric ton/kg.

Appendix K.37 Total carbon dioxide emissions from hydrogen production

Total carbon dioxide emission from hydrogen production in:	2008	2009	2010
Metric ton	7758867.518	5627068.096	7376112.015
Million metric ton	7.758867518	5.627068096	7.376112015

Appendix K.38 Total argon production from Kuwait factories

Argon produces from (Kg)	2008	2009	2010
Kuwait Oxygen Company	7,076,041	14,514,956	15,422,141
Refrigeration and oxygen company Ltd	1126417726	968931362	1036701691
Kuwait Industrial gases corporation	20004028.33	17277938	20217821.67
Total	1,153,497,795	1,000,724,256	1,072,341,654

Source: Adapted by the author from (PAI, 2014)

Appendix K.39 Total nitrous oxide production from Kuwait factories

Total nitrous oxide produces from Kuwait Oxygen Company in:	2008	2009	2010
Kg	117934	126552.5	125191.5

Source: Adapted by the author from (PAI, 2014)

Appendix K.40 Total acetylene production from Kuwait factories

Total acetylene produces from Kuwait oxygen company in	2008	2009	2010
Kg	117934	126552.5	125191.5

Source: Adapted by the author from (PAI, 2014)

Appendix K.41 Total argon, nitrous oxide, and acetylene production from Kuwait factories

Total production of argon, nitrous oxide, and acetylene in	2008	2009	2010
Kg	1,153,733,663	1,000,977,361	1,072,592,037

Source: Adapted by the author from (PAI, 2014)

Notes:

Due to lack of emission factors of argon, nitrous oxide and acetylene, these gases will be added to other chemical category.

Notes:

Other chemical includes (catalysts, oil demulsifier, scale inhibitor, corrosion inhibitor, other products, pharmaceutical, glue and artificial sponge, perfume, argon, nitrous oxide, acetylene and distilled water).

Appendix K.42 Total other chemicals production from Kuwait factories

	2008	2009	2010	Average
Pharmaceutical products	3,807	4665	5743	4,738
Total production of Glue	17933981.6	17176864.6	14024905.6	16378583.93
Total production of Artificial sponge	29,236,909.05	29,793,310.48	34,284,624.00	31,104,947.84
Total production of catalyst, oil demulsifier, scale inhibitors, corrosion, foam inhibitors and other products	14,339,000.00	12,824,000.00	9,892,000.00	12,351,666.67
Total production of argon, nitrous oxide and acetylene	1,153,733,663	1,000,977,361	1,072,592,037	1,075,767,687

Source: Adapted by the author from (PAI, 2014)

Notes:

Emission factor for other chemical is 0.003 metric ton/kg.

Appendix K.43 Total carbon dioxide associated with other chemical production

Carbon dioxide associated with other chemical production	2008	2009	2010
Metric ton	3,648,733.56	3185436.445	3395257.446
Million metric ton	3.648733565	3.185436445	3.395257446

Appendix L. Power Stations

Appendix L.1 Total fuel (million ton) in Kuwait power stations

Fuel (million ton)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	0.08821029	0.48816174	0.444555293	0.784523521	1.221547298	1.024174323	1.154825517	1.342665988	1.041044386
Heavy fuel oil	5.223572985	5.972554983	5.461836901	6.283630762	4.992576303	4.947818399	4.387985094	4.345436786	5.293192283
Gas natural	2.28448514	3.11265658	3.23702284	3.63183715	3.7830472	5.28575334	6.08040695	6.65470822	6.38711248
Crude oil	2.177746504	1.169056372	1.867943107	1.066645431	2.264262462	2.024466389	2.191724685	1.867088954	1.276198458

Appendix L. 2 Total fuel (ton) in Kuwait power stations

Fuel (ton)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	88210.29	488161.7405	444555.293	784523.5209	1221547.298	1024174.323	1154825.517	1342665.988	1041044.386
Heavy fuel oil	5223572.985	5972554.983	5461836.901	6283630.762	4992576.303	4947818.399	4387985.094	4345436.786	5293192.283
Gas natural	2284485.14	3112656.58	3237022.84	3631837.15	3783047.2	5285753.34	6080406.95	6654708.22	6387112.48
Crude oil	2177746.504	1169056.372	1867943.107	1066645.431	2264262.462	2024466.389	2191724.685	1867088.954	1276198.458

Notes:

Emission factor for gas oil is 0.875.

Emission factor for natural gas is 0.75.

Emission factor for Heavy fuel oil and crude oil is 0.85.

1 ton of carbon equal 3.666667 of carbon dioxide.

Appendix L. 3 Total carbon dioxide (ton) from fuel consumption in Kuwait power stations

Carbon dioxide (ton) from	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	283008.0137	1566185.584	1426281.565	2517012.963	3919130.915	3285892.62	3705065.201	4307720.046	3340017.406
Heavy fuel oil	16280135.8	18614463.03	17022725.01	19583982.54	15560196.14	15420700.68	13675886.88	13543277.98	16497115.95
Gas natural	6282334.135	8559805.595	8901812.81	9987552.163	10403379.8	14535821.69	16721119.11	18300447.61	17564559.32
Crude oil	6787309.937	3643559.025	5821756.017	3324378.26	7056951.34	6309586.913	6830875.267	5819093.906	3977485.196

Appendix L.4 Total carbon dioxide (million ton) from fuel consumption in Kuwait power stations

Carbon dioxide (million ton) from	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	0.283008014	1.566185584	1.426281565	2.517012963	3.919130915	3.28589262	3.705065201	4.307720046	3.340017406
Heavy fuel oil	16.2801358	18.61446303	17.02272501	19.58398254	15.56019614	15.42070068	13.67588688	13.54327798	16.49711595
Gas natural	6.282334135	8.559805595	8.90181281	9.987552163	10.4033798	14.53582169	16.72111911	18.30044761	17.56455932
Crude oil	6.787309937	3.643559025	5.821756017	3.32437826	7.05695134	6.309586913	6.830875267	5.819093906	3.977485196
Total	29.63278789	32.38401323	33.1725754	35.41292593	36.9396582	39.5520019	40.93294646	41.97053954	41.37917787

Appendix L.5 Total carbon dioxide (million metric ton) from fuel consumption in Kuwait power stations

Carbon dioxide (million metric ton) from	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	0.256740552	1.420819662	1.293900871	2.28339575	3.55537576	2.980942105	3.361178611	3.90789789	3.030012822
Heavy fuel oil	14.76909076	16.8867568	15.44275636	17.76629011	14.11597249	13.98942434	12.40655588	12.28625511	14.96593184
Gas natural	5.699237659	7.765325013	8.07558874	9.060554912	9.437787399	13.18667562	15.16914409	16.60188681	15.93430018
Crude oil	6.157344	3.305381147	5.281408219	3.015825227	6.401958567	5.723960963	6.196865803	5.278993192	3.608313873
Total	26.88241297	29.37828263	30.09365419	32.126066	33.51109422	35.88100303	37.13374439	38.075033	37.53855872

Appendix M. Road Transportation

Notes:

All gasoline and diesel that locally consumed is derived from Kuwait refineries except Euro4 Gasoline (95oct) that imported for ultra-cars.

Appendix M.1 Total fuel (million liter) locally consumed in Kuwait

Fuel (million litre)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Euro4 Gasoline (95oct)	0	0	0	0	0	0.092	0.082	0.096	0.1
Super Premium Gasoline	0	0	1949.8	2076.6	2191.9	2333	2479.3	2.675	2869.4
Premium Gasoline	0	0	1064.5	1046.4	992.8	956.8	891	837	804.7
Ultra-Super gasoline (98oct)	0	0	22.8	26.4	35.9	46.7	53.5	64.4	74.1
Total Gasoline Sales	2737.892	2877.247	3037.1	3149.4	3220.6	3336.5	3423.9	3576.6	3748.4
Diesel (Gas oil)	956.077	1048.162	1118.8	1136.7	1286.5	1400.4	1389.7	1595.1	1591.8

Source: (KNPC, 2016)

Notes:

Million Liter = 264172 Gallon.

Appendix M.2 Total fuel (gallon) locally consumed in Kuwait

Fuel (gallon)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total Gasoline	723274405.4	760088094.5	802316781.2	831983296.8	850792343.2	881409878	904498511	944837575	990222324.8
Total Diesel	252568773.2	276895051.9	295555633.6	300284312.4	339857278	369946468.8	367119828	421380757	420508989.6

Notes:

Since factories are also consume diesel from gas stations, the total amount of diesel seals was decreased by 20% to estimate carbon dioxide emitted from heavy vehicles.

Appendix M.3 Total fuel (gallon) locally consumed in Kuwait after modification

Fuel (gallon)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total Gasoline	723274405.4	760088094.5	802316781.2	831983296.8	850792343.2	881409878	904498511	944837575	990222324.8
Total Diesel	202055018.6	221516041.5	236444506.9	240227449.9	271885822.4	295957175	293695863	337104606	336407191.7

Notes:

Emission factor for gasoline is 0.00979 ton CO_2/ gallon.

Emission factor for diesel is 0.0112 ton CO_2/ gallon.

Appendix M.4 Total carbon dioxide (metric ton) from fuel locally consumed in Kuwait

Carbon dioxide (metric ton) from:	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gasoline	7080856.429	7441262.445	7854681.288	8145116.476	8329257.04	8629002.706	8855040.4	9249959.9	9694276.56
Diesel	2263016.208	2480979.665	2648178.477	2690547.439	3045121.211	3314720.36	3289393.7	3775571.6	3767760.547
Total	9343872.637	9922242.11	10502859.77	10835663.91	11374378.25	11943723.07	12144434	13025531	13462037.11

Appendix M.5 Total carbon dioxide (million metric ton) from local fuel consumption in Kuwait

Carbon dioxide (million metric ton) from:	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gasoline	7.08	7.441	7.855	8.145	8.329	8.629	8.855	9.25	9.694
Diesel	2.263	2.48	2.648	2.690	3.045	3.315	3.29	3.775	3.767
Total	9.343	9.922	10.502	10.835	11.374	11.943	12.144	13.025	13.462

Appendix M.6 Total carbon dioxide (million metric ton) from local fuel consumption in Kuwait

Carbon dioxide (million metric ton) from:	2014 (Est.)	2015 (Est.)	2016 (Est.)
Gasoline	10.153	10.634	11.665
Diesel	4.04	4.334	4.649
Total	14.193	14.968	16.314

Appendix N. Sulaibiy industrial area

Appendix N.1 Total asphalt production in Sulaibiy industrial area

Company	Location	Product	Unit	Production			
				2008	2009	2010	Average
Bisha for Asphalt Production Company	Sulaibiya	Asphalt	Kg	983,801,934	373,164,093	1,198,883,643	851,949,890
United Gulf for Asphalt Production	Sulaibiya	Asphalt	Kg	138,914,478	123,495,966	112,168,857	124,859,767
Saad Al-Bouss Est. Trading and General Contractings	Sulaibiya	Asphalt	Kg	129,507,879	162,707,212	289,593,327	193,936,139
The Kuwait Company for process Plant Constriction	Sulaibiya	Asphalt	Kg	172,365,101	199,580,643	149,685,482	173,877,075
Medco General Trading and Contracting company	Sulaibiya	Asphalt	Kg	653,173,013	653,173,013	653,173,013	653,173,013
United gulf for asphalt production company	Sulaibiya	Asphalt	Kg	138,914,478	123,495,966	112,168,857	124,859,767.00
Alhajraf asphalt factory	Sulaibiya	Asphalt	Kg	326,586,506	234,144,381	335,658,354	298,796,414
Total				2,543,263,389	1,869,761,274	2,851,331,533	

Source: Adapted by the author from (PAI, 2014)

Appendix N.2 Anticipated carbon dioxide emission from asphalt production in Sulaibiy industrial area

Anticipated carbon dioxide emission from asphalt production in:	2008	2009	2010
Metric ton	4730469.904	3477755.97	5303476.651
Million metric ton	4.730469904	3.47775597	5.303476651

Appendix N.3 Total plastic production in Sulaibiy industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Nooras Plastic Factory	Sulaibiya	Packing and garbage bags	Kg	4,535,924	3,628,739	2,721,554	3,628,739
		Table Sheets	Kg	907,185	680389	453592	680,389
Total				5,443,109	4,309,128	3,175,146	

Source: Adapted by the author from (PAI, 2014)

Appendix N.4. Total anticipated carbon dioxide emissions from plastic production in Sulaibiy industrial area

Anticipated carbon dioxide emission from plastic production in:	**2008**	**2009**	**2010**
Metric ton	14696.3943	11634.6456	8572.8942
Million metric ton	0.014696394	0.011634646	0.008572894

Appendix O. Amghara industrial area

Appendix O.1 Total asphalt production in Amghara industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Barco Asphalt Factory	Amghara	Asphalt for Roads	Kg	83,460,996	68,946,040	53,523,900	68,643,645
Naser Mohammed Al-Sayer Asphalt Production	Amghara	Asphalt	Kg	974,946,904	1,190,163,783	1,260,243,804	1,141,784,830
Jalfar Engineering and Contracting Co.	Amghara	Asphalt	Kg	136,077,711	108,862,169	108,862,169	117,934,016
Copri Constriction Enterprises Company	Amghara	Asphalt	Kg	128,224,213	104,660,996	24,719,877	85,868,362
Al-Khaled for asphalt factory	Amghara	Asphalt	Kg	87,089,735	783,807,615	68,038,856	312,978,735
				1,409,799,559	2,256,440,603	1,515,388,606	

Source: Adapted by the author from (PAI, 2014)

Appendix O.2 Anticipated carbon dioxide emissions from asphalt production from Amghara industrial area

Anticipated carbon dioxide emission from asphalt production in:	2008	2009	2010
Metric ton	2622227.18	4196979.522	2818622.807
Million metric ton	2.62222718	4.196979522	2.818622807

Appendix O.3 Total detergent production in Amghara industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Ghanim Detergent and Aerosol Manufacture	Amghra	Dish and Glass cleaner Antiseptic	Kg	14520000	16440000	6060000	12,340,000.00
		Cloth Softener and Bath Cleaner	Kg	2400000	1800000	1740000	1,980,000.00
				16920000	18240000	7800000	

Source: Adapted by the author from (PAI, 2014)

Appendix O.4 Anticipated carbon dioxide emissions from detergents production in Amghara industrial area

Anticipated carbon dioxide emission from detergents production in:	2008	2009	2010
Metric ton	29610	31920	13650
Million metric ton	0.02961	0.03192	0.01365

Appendix O.5 Total Plastic (Buildings boats) production in Amghara industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
United Fiberglass Factory	Amghara	Fiberglass and Polyethylene Tanks	Kg	200000	182,500.00	172,500.00	185,000.00
		Fiberglass Plant Pots and Pipes	Kg	73.3	57.87	46.295	59.155
		Boat Decoration	Kg	3,800	3,200	3,400	3,467
Total				203873.3	185,757.87	175,946.30	

Source: Adapted by the author from (PAI, 2014)

Appendix O.6 Total plastic (Floor) production in Amghara industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait polyurethane industry company	Amghara	Polyurethane materials	Kg	3,265,865	3,810,176	4,263,768	3,779,936.33
		Insulation panels	Kg	240,000	432,000	440,000	370,666.67
Total				3,505,865	4,242,176	4,703,768	

Source: Adapted by the author from (PAI, 2014)

Appendix O.7 Total plastic (Cultry) production in Amghara industrial area

Company	Location	Product type	unit	Production			
				2008	2009	2010	Average
Al-Khalid plastic Industries Company	Amghara	Plastic Bags	Kg	1,360,777	1,360,777	1,088,622	1,270,058.67
Genoa Plastic Industries	Amghara	PET preform	Kg	5,964,740	1,123,095	0	2,362,611.67
Total				7,325,517	2,483,872	1,088,622	

Source: Adapted by the author from (PAI, 2014)

Appendix O.8 Anticipated carbon dioxide emissions from plastic production in Amghara industrial area

Anticipated carbon dioxide emission from plastic production in:	2008	2009	2010
Metric ton	29795.18931	14894.70085	16114.508
Million metric ton	0.029795189	0.014894701	0.016114508

Appendix P. Sabhan industrial area

Appendix P.1 Total paint production in Sabhan industrial area

Company	Location	Product type	Unit	Production 2008	2009	2010	Average
International Warba Company for Paints	Sabhan	Industrial Paints	Kg	25680	18020	21660	21786.66667
		Marine Paints	Kg	147060	109730	108650	121813.3333
Seahawk Paints		Sea Dyes	Kg	0	0	9 109.71	3036.57
G.T.C paint Company Limited	Sabhan	Assorted Paints	Kg	13,561,911.52	12,599,550.07	10,921,731	12,361,064.08
International Powder Coating Company	Sabhan	Color Powder	Kg	397347	501673	695811	531610.3333
Al-Sanea chemical products	Sabhan	Detergents and disinfectant chemical	Kg	1,281,852	1,281,852	1,281,852	1,281,852
		Paints and white solvent	Kg	2,866,704	1,959,519	1,469,639	2,098,620.67
		Heating plumes	Kg	181,436,948	181,436,948	181,436,948	181,436,948
				199717502.5	197907292.1	195936290.7	

Source: Adapted by the author from (PAI, 2014)

Appendix P.2 Anticipated carbon dioxide emissions from paints production in Sabhan industrial area

Anticipated carbon dioxide emission from paints production in:	2008	2009	2010
Metric ton	1078474.514	1068699.377	1058055.97
Million metric ton	1.078474514	1.068699377	1.05805597

Appendix P.3 Total perfume production in Sabhan industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Perfumes Factory	Sabhan	Herbal, Palm, Rose and Flower water	Kg	84368.2	76203.5	78925.1	79832.26667
		Cologne Water, Eau De toilette and Perfumes	Kg	406419	393718	397347	399161.3333
		Scented Towels and medical alcohol wipes	Kg	7257.48	7257.48	9071.85	7862.27
Al-Shaya Perfumes Factory	Sabhan	Cologne and Rose, Flower and Plam water	Kg	367499.5	388305	239391.5	331732
				865544.18	865483.98	724735.45	

Source: Adapted by the author from (PAI, 2014)

Appendix P.4 Total pharmaceutical production in Sabhan industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait Saudi pharmaceutical industries	Sabhan	Injection bottles	Kg	2,347	2,522	3,875	2,915
		Pills and capsules	Kg	245.59	349.874	180.342	258.602
		Syrup	Kg	1214.75	1,792.65	1,688	1,565
				3,807	4,665	5,743	

Source: Adapted by the author from (PAI, 2014)

Appendix P.5 Total glue production in Sabhan industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
G.T.C. adhesives factory	Sabhan	Assorted adhesive materials, thermoplastic and foam tchechol compound	Kg	17933981.55	17176864.61	14024905.63	16378583.93

Source: Adapted by the author from (PAI, 2014)

Appendix P.6 Total sponge production in Sabhan industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Baghi United for Sponge Industries	Sabhan	Synthetic sponge and polyester products	Kg	0	0	1,756,310	585,437
		Spring mattresses and bed sheets	Kg	0	0	631,218.40	210,406.13
Abbas Ali Al-Hazeem and Partners	Sabhan	Spring mattresses	Kg	666,780	666,780	889040	740866.6667
		Divan beds and saloons	Kg	361174.1	361174.1	361174.1	361174.1
		Sponge and its derivatives	Kg	122,500	122,500	122,500	122,500
Al-Farres industries	Sabhan	Mattresses and headboard	Kg	42407.208	37072.968	84236.54	54572.23867
		Divan and seat sets	Kg	30220.69	17690.16	3,685.45	17,198.77
		Other miscellaneous	Kg	54061	13636	36883	34860
				1277142.998	1218853.228	3,885,047	

Source: Adapted by the author from (PAI, 2014)

Appendix P.7 Anticipated carbon dioxide emissions from paints production in Sabhan industrial area

Anticipated carbon dioxide emission from paints production in:	2008	2009	2010
Metric ton	60241.4282	57797.59903	55921.29574
Million metric ton	0.060241428	0.057797599	0.055921296

Appendix P.8 Total plastic (primar form) production in Sabhan industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Sulaiman Alqudaibi Co. for G.R.P and Plastic Product	Sabhan	GRP Pipes	Kg	13,333,320	13,333,320	13,333,320	13,333,320.00
		Jacking Pipe	Kg	119,988	119,988	119,988	119,988
		Manholes and Other Product	Kg	134,985	134,985	134,985	134,985
Al-Sanea for Plastic Pipes and Fitting Factory	Sabhan	Plastic	Kg	1,315,418	952,544	907,185	1,058,382.33
		Plastic junction	Kg	616886	401883	362874	460547.6667
				15,520,597	14,942,720	14,858,352	

Source: Adapted by the author from (PAI, 2014)

Appendix P.9 Total plastic (floor) production in Sabhan industrial area

Company	Location	Product type	Unit	2008	2009	2010	Average
Al-Ahlia plastic Company	Sabhan	Plastic Bags and Rolls	Kg	4,310,942	4,436,133	4,372,630	4,373,235.00

Source: Adapted by the author from (PAI, 2014)

Appendix P.10 Total plastic (curtly) production in Sabhan industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Shorouq Pack Soft	Sabhan	Packing and Packaging Materials	Kg	1,270,059	1,224,699	1,224,699	1,239,819.00
		Plastic Stickers	Kg	1,800	1,400	1,300	1,500
				1,271,859	1,226,099	1,225,999	

Source: Adapted by the author from (PAI, 2014)

Appendix P.11 Anticipated carbon dioxide emissions from plastic production in Sabhan industrial area

Anticipated carbon dioxide emission from plastic production in:	2008	2009	2010
Metric ton	20979.2106	19633.4064	19233.8847
Million metric ton	0.020979211	0.019633406	0.019233885

Appendix P.12 Anticipated carbon dioxide emissions from G.R.P production in Sabhan industrial area

Anticipated carbon dioxide emission from G.R.P production in:	2008	2009	2010
Metric ton	107999.892	107999.892	107999.892
Million metric ton	0.107999892	0.107999892	0.107999892

Appendix Q. Shwaikh industrial area

Appendix Q.1 Total paint production in Shwaikh industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Matrouk Paints Factory	Shwaikh	Decoration, Artificial and Marine Paints	Kg	687,090	868,840	791,229	782,386
		Other Paints	Kg	51,670	68,245	59,013	59,643
				738,760	937,085	850,242	

Source: Adapted by the author from (PAI, 2014)

Appendix Q.2 Anticipated carbon dioxide emissions from paints production in Shwaikh industrial area

Anticipated carbon dioxide emission from paints production in:	2008	2009	2010
Metric ton	3989.304	5060.259	4591.3068
Million metric ton	0.003989304	0.005060259	0.004591307

Appendix Q.3 Total plastic (Floor) production in Shwaikh industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Qitami insulation materials factory	Shuwaikh	Insulation blocks and polystyrene products	Kg	1,451,496	907,185	725748	1,028,143.00

Source: Adapted by the author from (PAI, 2014)

Appendix Q.4 Anticipated carbon dioxide emissions from plastic production in Shwaikh industrial area

Anticipated carbon dioxide emission from plastic production in:	2008	2009	2010
Metric ton	3919.0392	2449.3995	1959.5196
Million metric ton	0.003919039	0.0024494	0.00195952

Appendix R. Shuaiba industrial area

Appendix R.1 Total paints production in Shuaiba industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Abdul Aziz Abd Almohsen Al-Rashid Sons Factory	Shuaiba	Marble Polish and Primer	Kg	0	444521	489880	311467
		Striper and Coating	Kg	0	390089	417305	269131.3333

Source: Adapted by the author from (PAI, 2014)

Appendix R.2 Anticipated carbon dioxide emissions from paints production in Shuaiba industrial area

Anticipated carbon dioxide emission from paints production in:	2009	2010
Metric ton	2106.4806	2253.447
Million metric ton	0.002106481	0.002253447

Appendix R.3 Total detergents production in Shuaiba industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Sharhan Aerosol Establishment	Shuaiba	Aerosol products	Kg	3,068.75	3,496	4,374.75	3,646.50
		Detergent, Disinfectant, Antisepct	Kg	1,328	1,120.50	1,273.75	1,240.75
				4,396.75	4,617	5,648.50	

Source: Adapted by the author from (PAI, 2014)

Appendix R.4 Total lubricating oil production in Shuaiba industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Kuwait national lubricating oil company	Shuaiba	Automatic engine oils	Kg	2100000	1350000	1400000	1,616,666.67
		Industrial oils	Kg	2200000	1400000	1500000	1,700,000.00
		Engine oils	Kg	1465000	886000	962000	1,104,333.33
Kuwait lubricant oil company	Shuaiba	Greases and lubricants	Kg	19,402,867	14,762,617	12,585,374	15,583,619
		Water	Kg	3,257,700	2,694,339	1,680,106	2,544,048.33
Kuwait Dana for oil company	Shuaiba	Lubricant oils	Kg	44,497,411	44,497,411	44,497,411	44,497,411
		grease	Kg	5443.11	5443.11	5443.11	5443.11
Total				72928421.11	65595810.11	62630334.11	

Source: Adapted by the author from (PAI, 2014)

Appendix R.5 Anticipated carbon dioxide emissions from lubricant oil production in Shuaiba industrial area

Anticipated carbon dioxide emission from lubricant oil production in:	2008	2009	2010
Metric ton	78033.41059	70187.51682	67014.4575
Million metric ton	0.078033411	0.070187517	0.067014457

Appendix R.6 Total perfume production in Shuaiba industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
Al-Mubrouk Perfumes	Shuaiba	Oud Oil and Mammol	Kg	28000	25000	22000	25000
		Oriental Mixtures, French and Arabian perfumes	Kg	51000	66000	55500	57500
Tabahly Factory for perfumes	Shuaiba	Perfumes and Incense	Kg	0	0	17000	5666.666667
		Mixture	Kg	0	0	34	11.33333333
Total				79000	91000	94534	

Source: Adapted by the author from (PAI, 2014)

Appendix R.7 Total sponge production in Shuaiba industrial area

Company	Location	Product type	Unit	Production			
				2008	2009	2010	Average
National sponge factory and bed health	Shuaiba	Sponge sheet	Kg	35600	38600	42500	38900
		Sponge Mattresses	Kg	8,179,168	8,579,236	9,023,756	8,594,053.33
				8214768	8617836	9066256	

Source: Adapted by the author from (PAI, 2014)

Appendix R.8 Anticipated carbon dioxide emissions from lubricant oil production in Shuaiba industrial area

Anticipated carbon dioxide emission from lubricant oil production in:	2008	2009	2010
Metric ton	24881.304	26126.508	27482.37
Million metric ton	0.024881304	0.026126508	0.02748237

Appendix R.9 Total inorganic acid production in Shuaiba industrial area

Company	Location	Product type	Unit	2008	2009	2010	Average
Chemkuwait for chemical industries	Shuaiba	Concentrated and diluted sulphuric acid	Kg	52,303,736	44,402,157	44,444,795	47,050,229

Source: Adapted by the author from (PAI, 2014)

Appendix R.10 Anticipated carbon dioxide emissions from Sulphur acid production in Shuaiba industrial area

Anticipated carbon dioxide emission from Sulphur acid production in:	2008	2009	2010
Metric ton	7322.52304	6216.30198	6222.2713
Million metric ton	0.007322523	0.006216302	0.006222271

Appendix R.11 Total fertilizers production in Shuaiba industrial area

Company	Location	Product type	Unit	2008	2009	2010	Average
Petrochemical industries company	Shuaiba	Urea	Kg	662,716,596	799,111,822	926,056,904	795,961,774.03
		Amonia	Kg	444,801,750	520,007,365	576,851,561	513,886,892.00
Total				1,107,518,346	1,319,119,187	1,502,908,465	1,309,848,666

Source: Adapted by the author from (PAI, 2014)

Appendix R.12 Anticipated carbon dioxide emissions from lubricant oil production in Shuaiba industrial area

Anticipated carbon dioxide emission from lubricant oil production in:	2008	2009	2010
Metric ton	5116734.759	6094330.644	6943437.108
Million metric ton	5.116734759	6.094330644	6.943437108

Notes:

Shuaiba refinery (SHU) emits 2.921 Mt.

Shuaiba refinery terminals emit 0.019 Mt.

United Steel Company emits 0.197040526 Mt.

Kuwait cement company emits 0.322 Mt.

Shuaiba Port emits 0.08968263 Mt.

Appendix R.13 Total fuel consumption in North Shuaiba power plant

Consumption of fuel in North Shuaiba power station (ton)	2013
Consumption of natural gas	709689.16
Consumption of gas oil	11003.6899

Appendix R.14 Total fuel consumption in Shuaiba South power plant

Consumption of fuel in Shuaiba South power station (ton)	2013
Consumption of natural gas	994388.33

Appendix R.15 Anticipated carbon dioxide emissions in 2013 from consumption of natural gas and gas oil in North and South Shuaiba power plants

Anticipated carbon dioxide emission in 2013 from consumption of:	North Shuaiba power plant (ton)	Shuaiba South power plant (ton)
Natural gas	1951645.367	2734568.156
Gas oil	35303.5083	

Appendix R.16 Anticipated carbon dioxide emissions in 2013 from consumption of natural gas and gas oil in North and South Shuaiba power plants

Anticipated carbon dioxide emission in 2013 from consumption of:	North Shuaiba power plant (million metric ton)	Shuaiba South power plant
Natural gas	1.770502895	2.480758502
Gas oil	0.032026804	
	1.802529699	

Appendix S. Doha industrial area

Appendix S.1 Total fuel consumption in Doha East power station

Consumption of fuel in Doha East power station (ton)	2013
Consumption of natural gas (ton)	363,674
Consumption of Gas Oil (ton)	4.43E-05
Consumption of Crude Oil (ton)	442389.9879
Consumption of Heavy Oil (ton)	370586.6766

Appendix S.2 Total fuel consumption in Doha West power station

Consumption of fuel in Doha West power station (ton)	2013
Consumption of natural gas	375027.78
Consumption of heavy oil	2018142.116

Appendix S.3 Anticipated carbon dioxide emissions (ton) in 2013 from fuel consumption in Doha East and West power stations

Anticipated carbon dioxide emission (ton) in 2013 from consumption of:	Doha East Power Station	Doha West Power Station
Consumption of natural gas	1000103.308	1031326.395
Consumption of heavy oil	1154995.142	6289876.262
Consumption of gas oil	1.42E-04	
Consumption of crude oil	1378782.129	

Appendix S.4 Anticipated carbon dioxide emissions (metric ton) in 2013 from fuel consumption in Doha East and West power stations

Anticipated carbon dioxide emission (metric ton) in 2013 from consumption of:	Doha East Power Station	Doha West Power Station
Consumption of natural gas	907278.4594	935603.5675
Consumption of heavy oil	1047793.968	5706079.761
Consumption of gas oil	1.29E-04	
Consumption of crude oil	1250810.107	

Appendix S.5 Anticipated carbon dioxide emissions (Mt) in 2013 from fuel consumption in Doha East and West power stations

Anticipated carbon dioxide emission (Mt) in 2013 from consumption of:	Doha East Power Station	Doha West Power Station
Consumption of natural gas	0.907278459	0.935603568
Consumption of heavy oil	1.047793968	5.706079761
Consumption of gas oil	1.29E-10	
Consumption of crude oil	1.250810107	
Total	3.205882534	6.641683329

Notes:

Doha port emit 0.044841314 Mt.

Appendix T. Al-Zour industrial area

Appendix T.1 Total fuel consumption in South Al-Zour power station

Consumption of fuel in South Al-Zour power station (ton)	2013
Consumption of natural gas	2460216.35
Consumption of Gas Oil (ton)	307778.065
Consumption of Crude Oil (ton)	824363.5344
Stations Consumption of Heavy Oil (ton)	1009946.737

Appendix T.2 Anticipated carbon dioxide emissions (ton) from fuel consumption in South Al-Zour power station

Anticipated carbon dioxide emission (ton) from consumption of:	2013
Consumption of natural gas	6765595.578
Consumption of gas oil	987454.715
Consumption of crude oil	2569266.582
Stations Consumption of heavy oil	3147667.616

Appendix T.3 Anticipated carbon dioxide emissions (metric ton) from fuel consumption in South Al-Zour power station

Anticipated carbon dioxide emission (metric ton) in 2013 from consumption of:	Metric ton	Million metric ton
Consumption of natural gas	6137645.065	6.137645065
Consumption of gas oil	895803.8489	0.895803849
Consumption of crude oil	2330799.436	2.330799436
Stations Consumption of heavy oil	2855516.028	2.855516028
Total		12.21976438

Notes:

Al-Zour terminal emits 0.019 Mt.

Appendix U. Sabiya industrial area

Appendix U.1 Total fuel consumption in Sabiya power station

Total fuel consumption in Sabiya power station	2013
Consumption of natural gas	1298077.31
Consumption of gas oil	722218.227
Consumption of crude oil	9444.9362
Consumption of heavy oil	1894516.75

Appendix U.2 Anticipated carbon dioxide emissions (ton) in 2013 from fuel consumption in Sabiya power station

Anticipated carbon dioxide emission (ton) from consumption of:	2013
Consumption of natural gas	3569712.927
Consumption of gas oil	2317117.022
Consumption of crude oil	29436.7205
Consumption of heavy oil	5904577.741

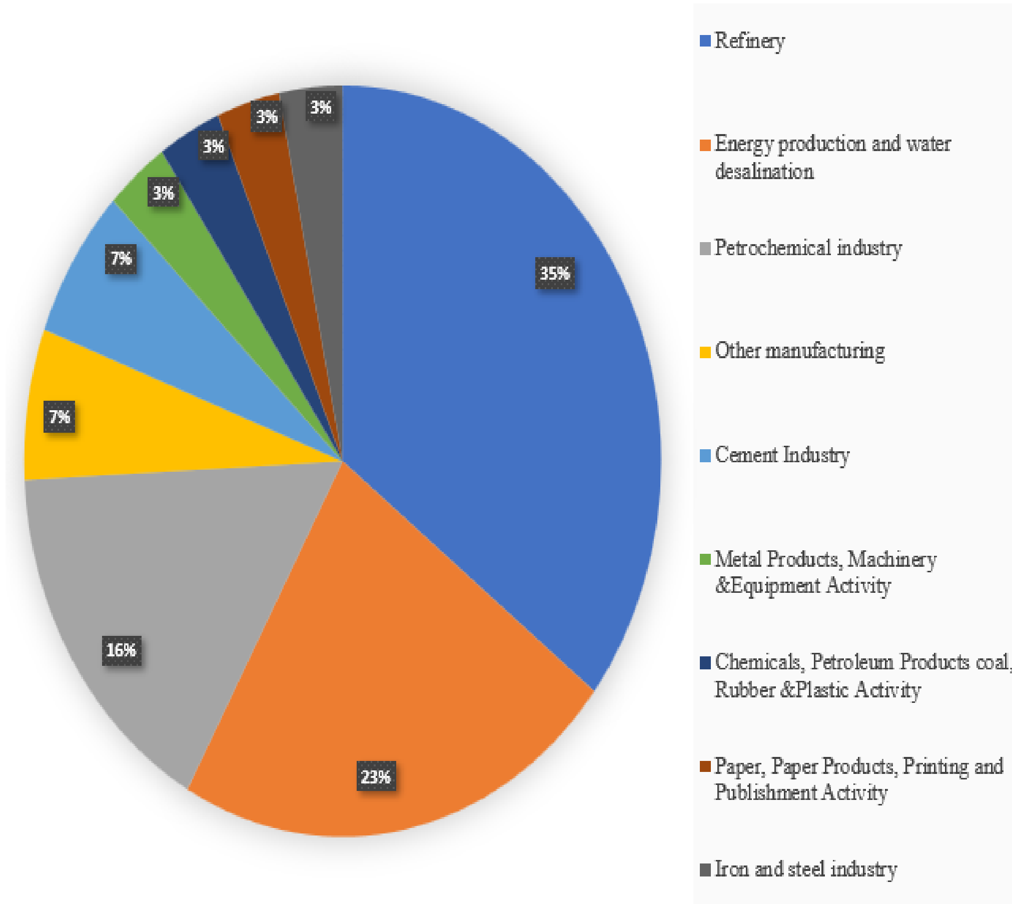
Appendix U.3 Anticipated carbon dioxide emissions (metric ton) in 2013 from fuel consumption in Sabiya power station

Anticipated carbon dioxide emission (metric ton) from consumption of:	2013
Consumption of natural gas	3.238389094
Consumption of gas oil	2.102053203
Consumption of crude oil	0.026704543
Consumption of heavy oil	5.356542823
	10.72368966

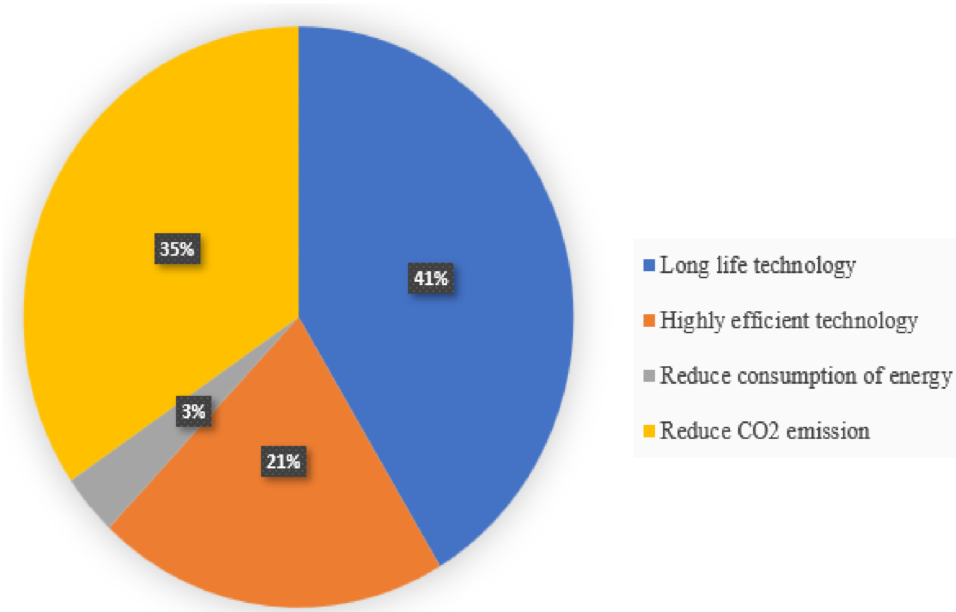
Appendix V. The carbon footprint of other industrial areas

Location	Stationary Sources	Anticipated carbon dioxide emission (metric ton)
Al-Ahmidi	Equate Petrochemical Co.	2.64279661
	Burgan oil field	0.168057942
Mina Alahmadi	Mina Alahmadi refinery	3.429158
Mina Abdullah	Mina Abdullah refinery	2.88
	Mina Abdullah terminal	0.089682627
Kuwait City	Kuwait international airport	0.138598831
Minagish	Minagish oil field	0.006302173
Um Gudair	Um Gudair oilfield	0.006302173
Raudatin	Raudatin oilfield	0.026259053
Sabiriyah	Sabiriyah oilfield	0.016805794

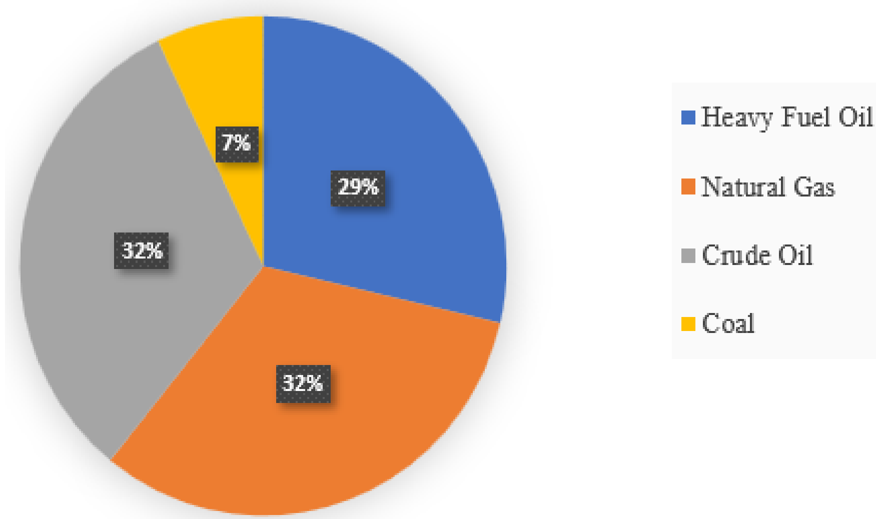
Appendix W. Information-Choice Questionnaires (ICQ) results



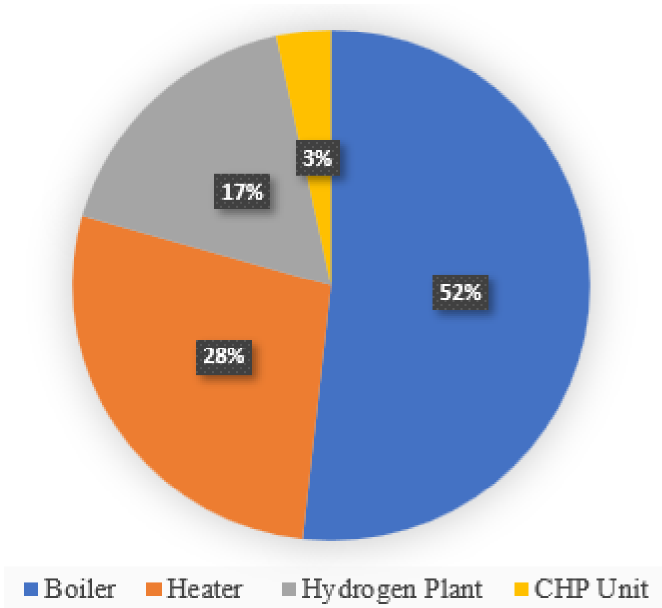
Appendix W.1 Views on basic information. Question: What is the best description of the production process in your facility?



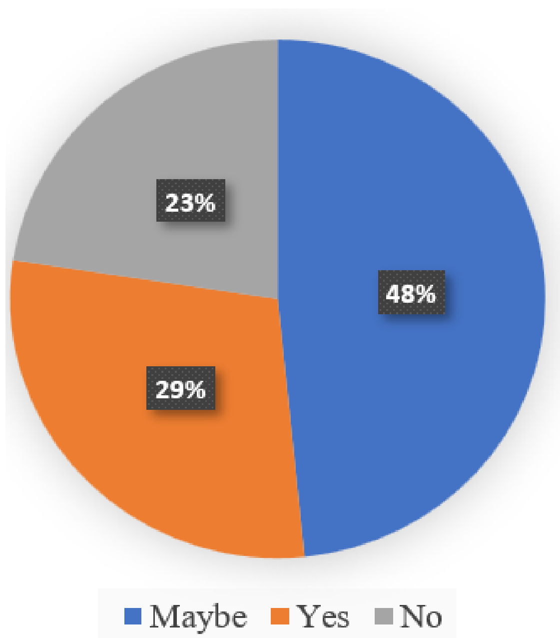
Appendix W.2 Views on basic information. Question: What are the advantages of your technology over other technologies in the market?



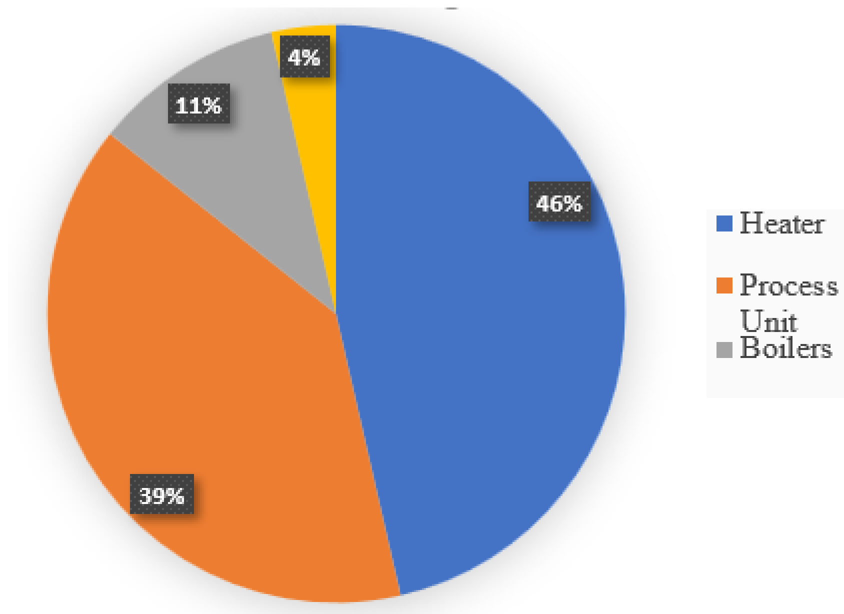
Appendix W.3 Views on basic information. Question: What is the type of fuel used in your facility?



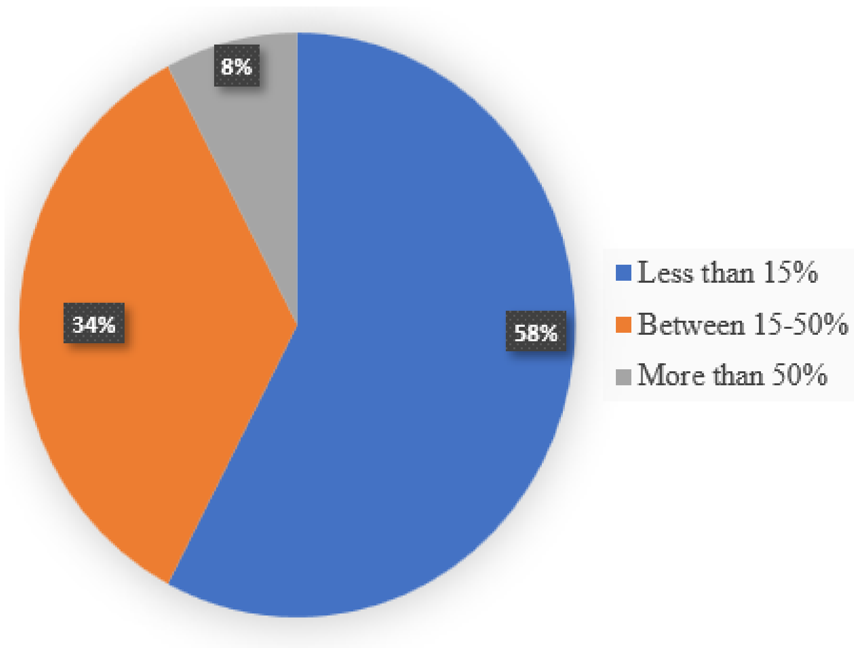
Appendix W.4 Views on basic information. Question: Which type of distributed energy system is used in your facility?



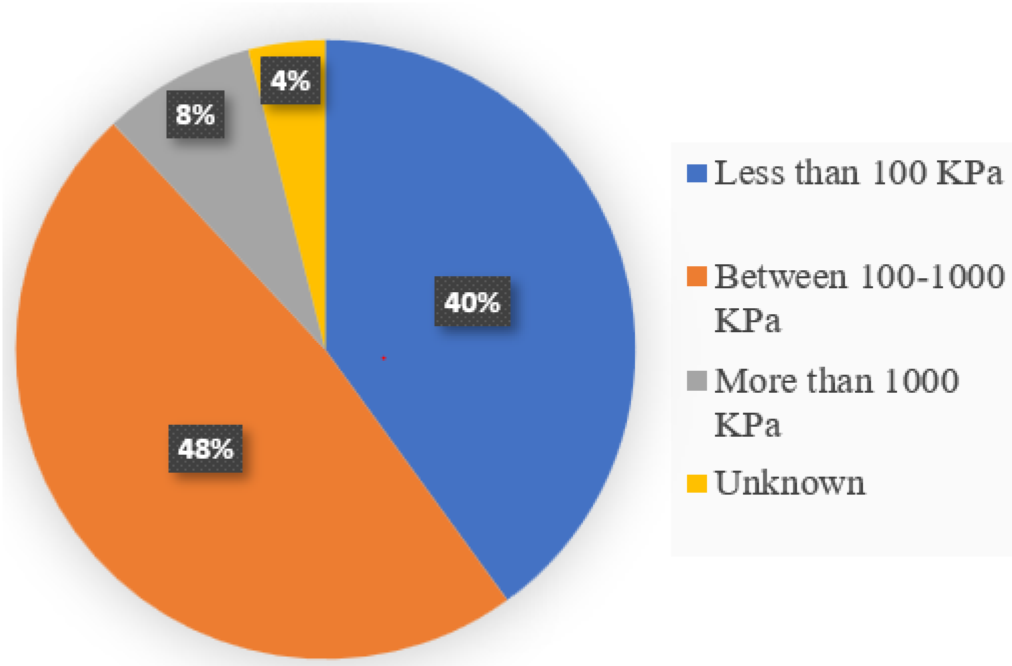
Appendix W.5 Views on basic information. Question: Can you allocate space for carbon-capturing facilities?



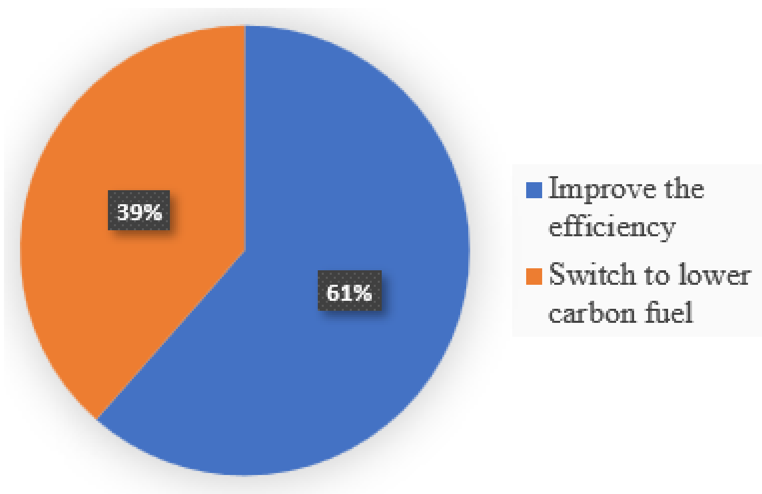
Appendix W.6 Views on the carbon footprint. Question: What are the main emission sources of CO_2 in your facility?



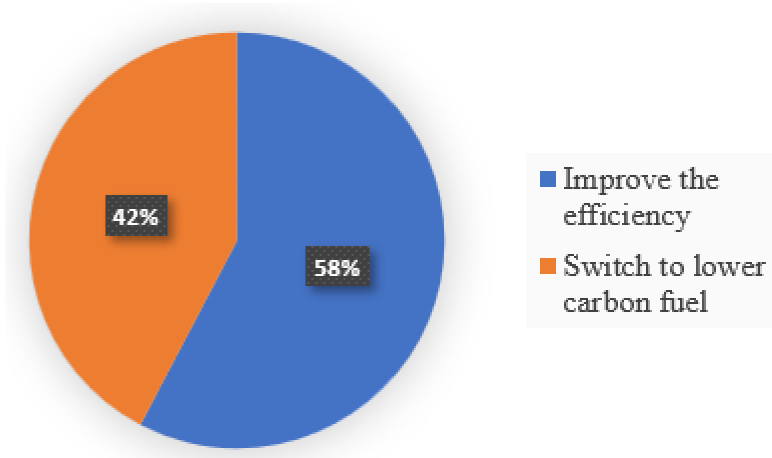
Appendix W.7 Views on the carbon footprint. Question: What is the concentration of CO_2 flow gas from these sources?



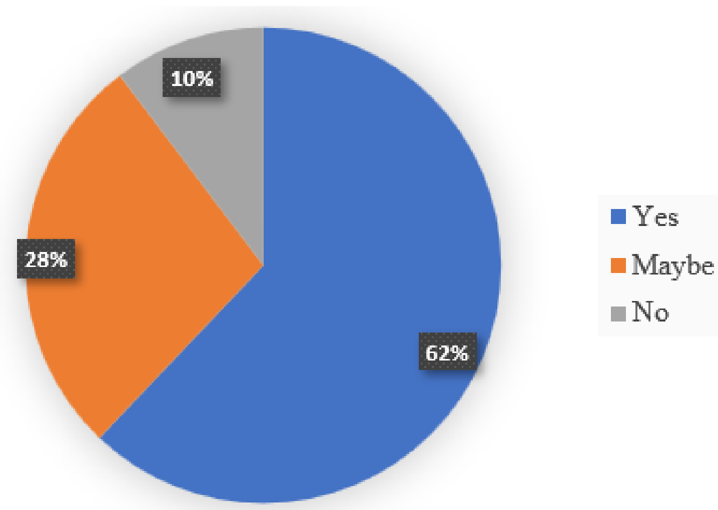
Appendix W.8 Views on the carbon footprint. Question: What the typical partial pressure in the flowing gas in your facility?



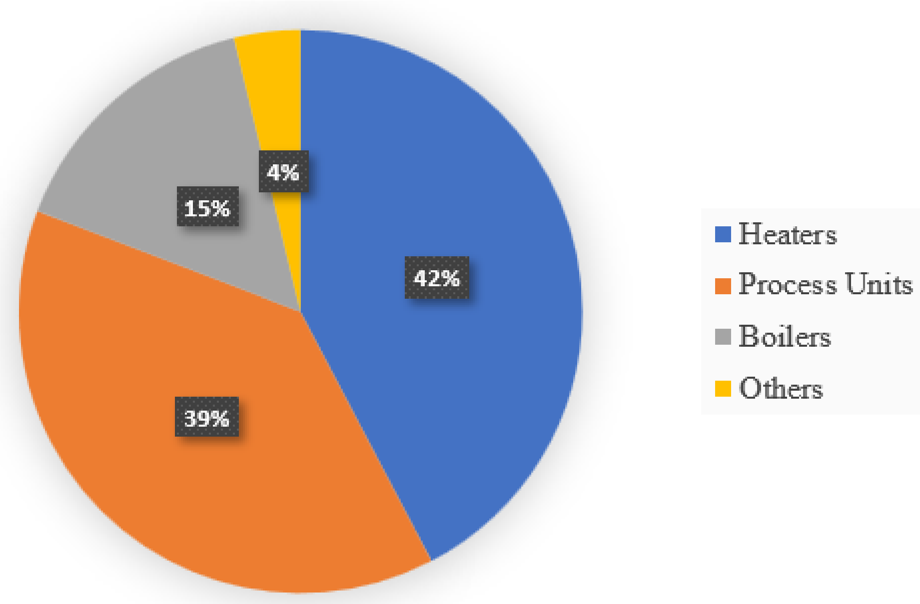
Appendix W.9 Views on carbon dioxide abatement practices Question: What is the current carbon abatement strategy utilised in your facility?



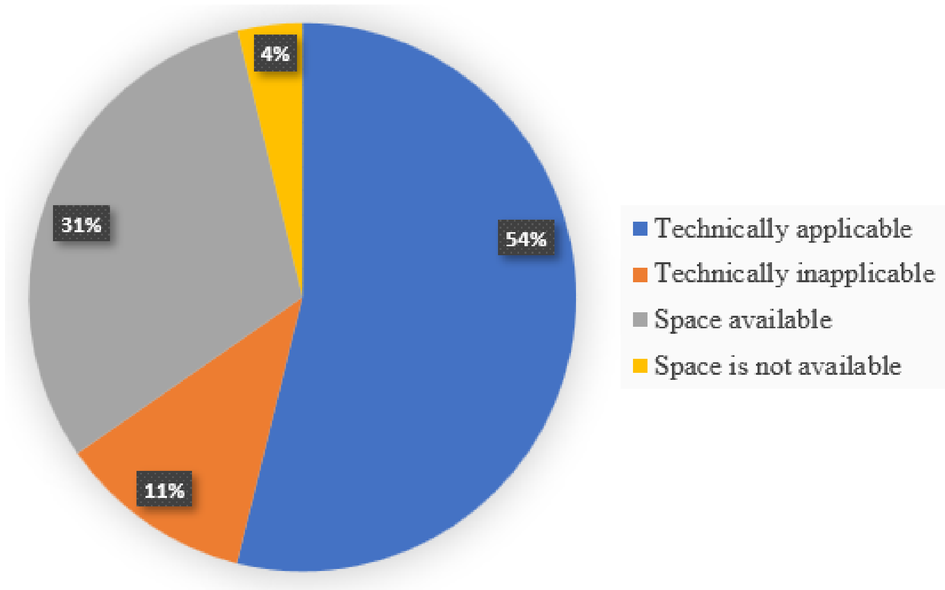
Appendix W.10 Views on carbon dioxide abatement practices Question: What is your long-term objective for carbon abatement?



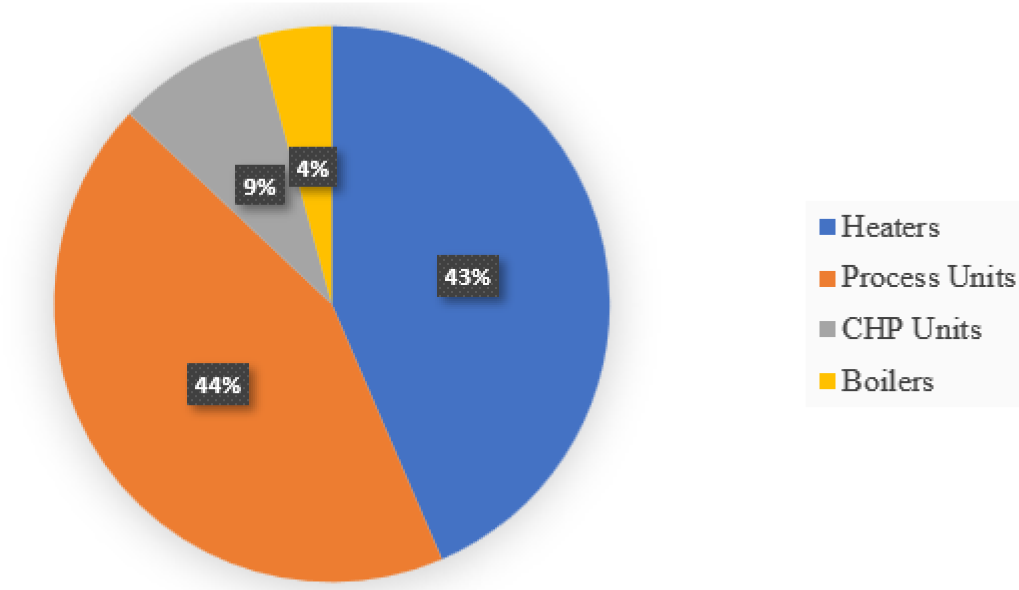
Appendix W.11 Views on carbon dioxide abatement practices. Question: If Kuwait Environmental Public Authority (KEPA) introduces a carbon tax, would you think of constructing a carbon capture unit?



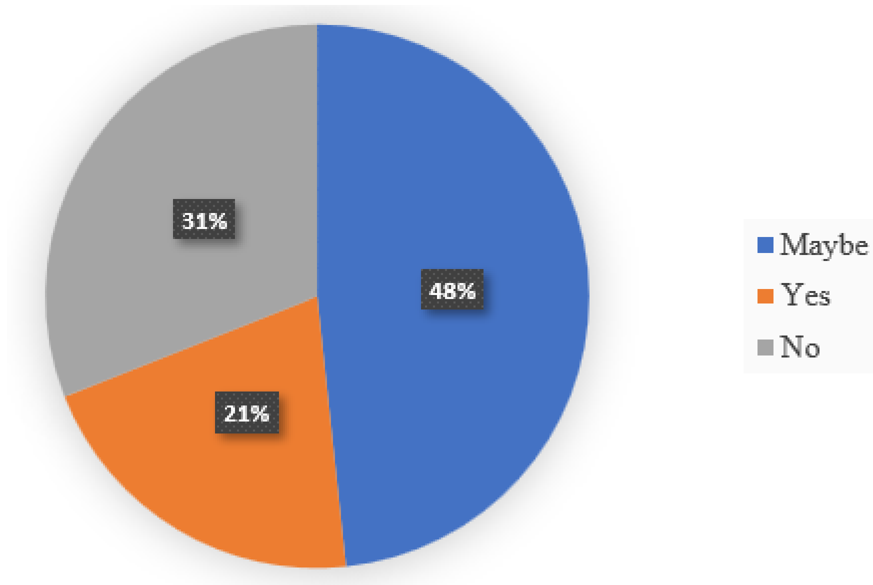
Appendix W.12 Views on post-combustion- if applicable. Question: Which units in your facility produce excess energy that can be reused in the capture unit?



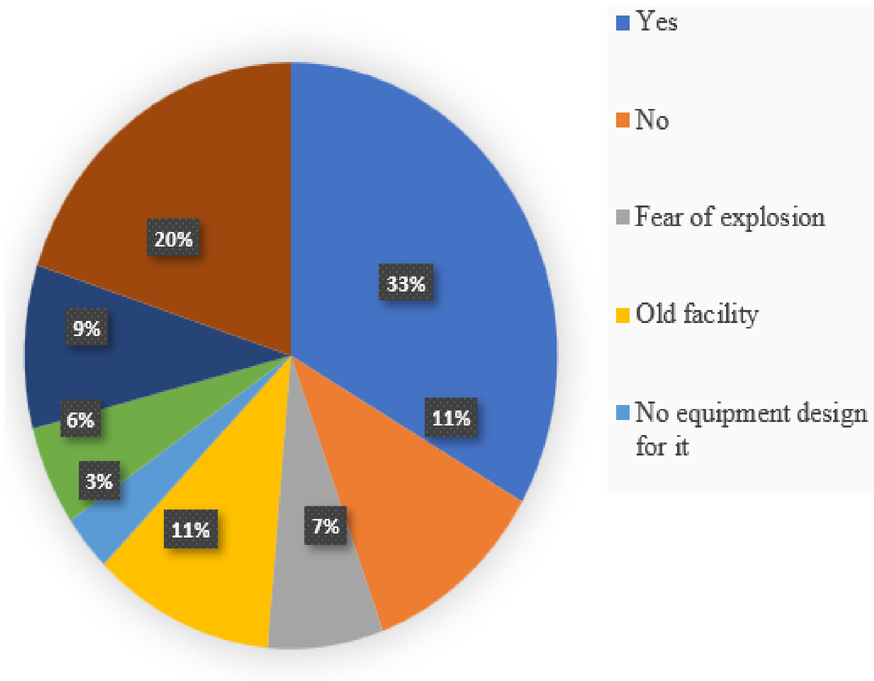
Appendix W.13 Views on oxy-fuel combustion- if applicable. Question: What are the technical and spatial constraints of deploying the Air Separation Unit (ASU) in your facility?



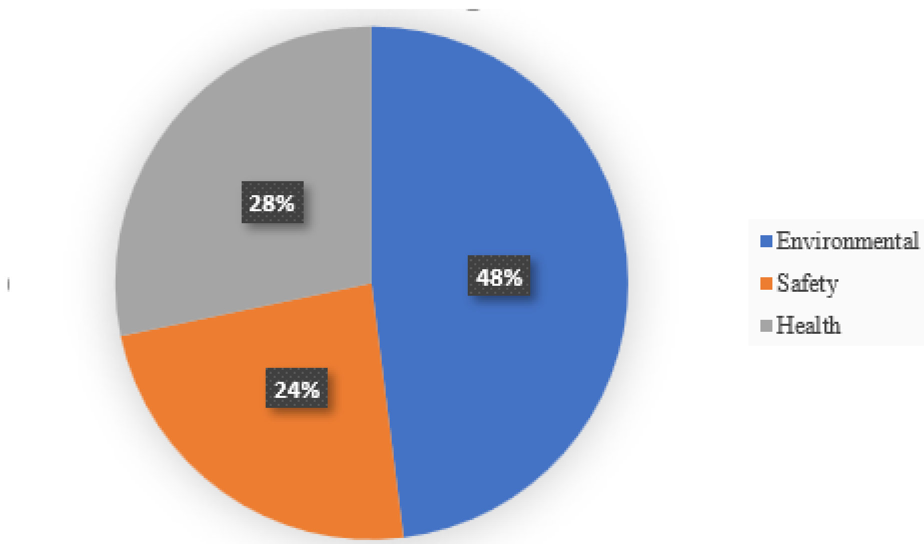
Appendix W.14 Views on oxy-fuel combustion- if applicable. Question: Which units in your facility need to be modified to work on full-oxy fuel combustion mode?



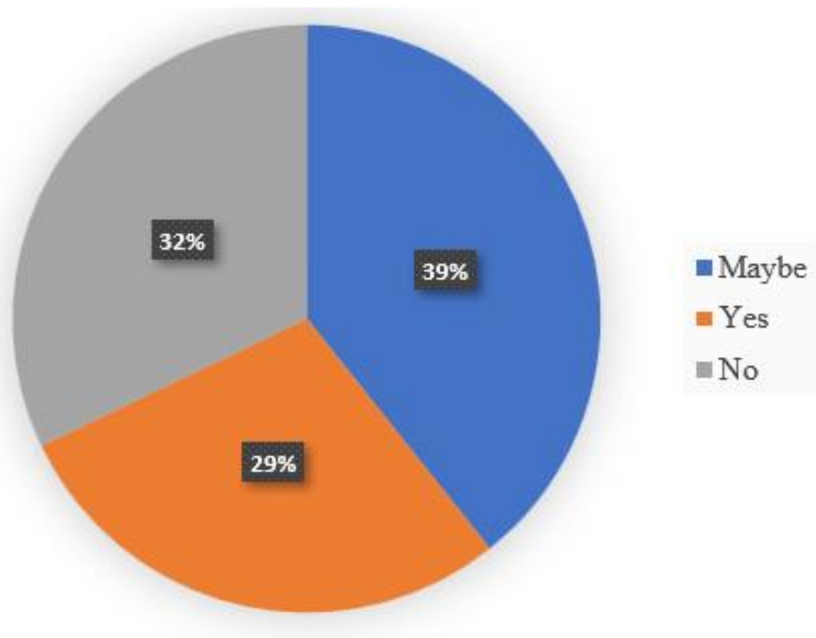
Appendix W.15 Views on oxy-fuel combustion- if applicable. Question: From a technical perspective, can you recycle back the CO_2 to the generator to reduce the combustion temperature?



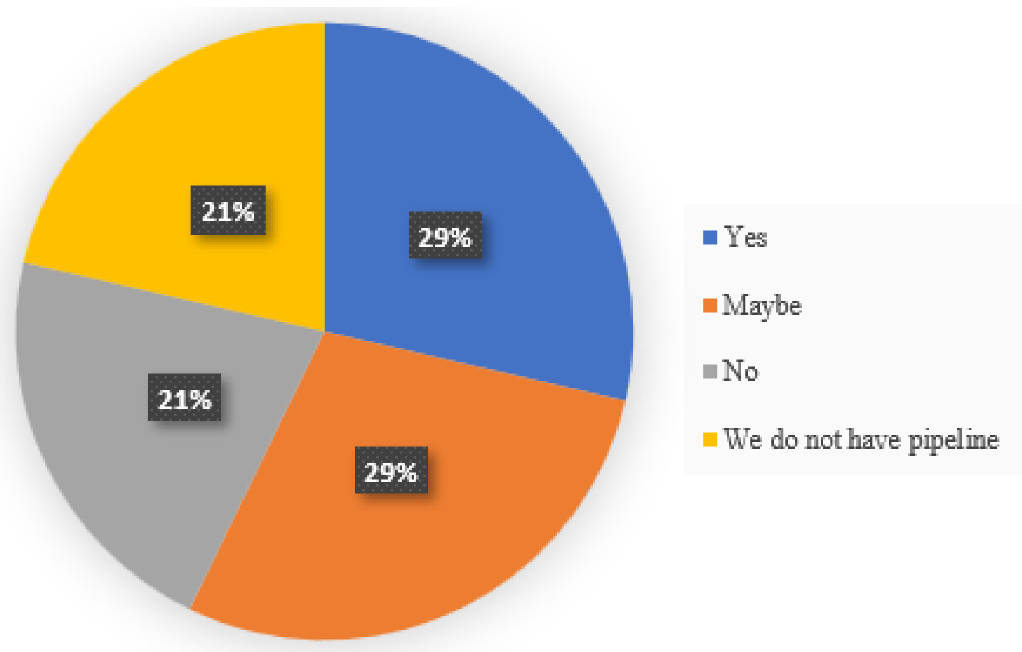
Appendix W.16 Views on pre-combustion - if applicable. Question: Can hydrogen be used as the primary fuel in your utilities? If no, what are the technical barriers?



Appendix W.17 Views on the risks associated with deploying carbon capture technologies. Question: In your opinion, what are the potential risks associated with deploying carbon capture technologies in your facility?

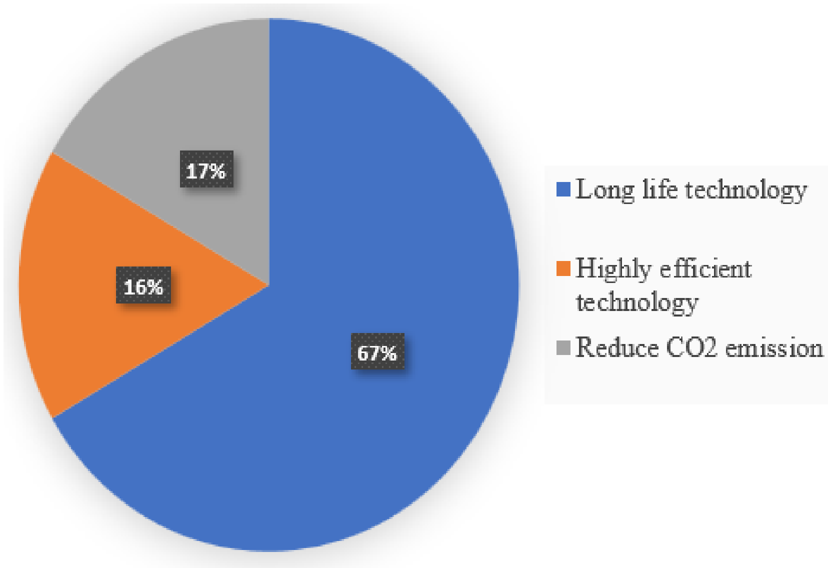


Appendix W.18 Views on the utilization pathways. Question: Can you utilize the captured CO_2 from your production pathway?

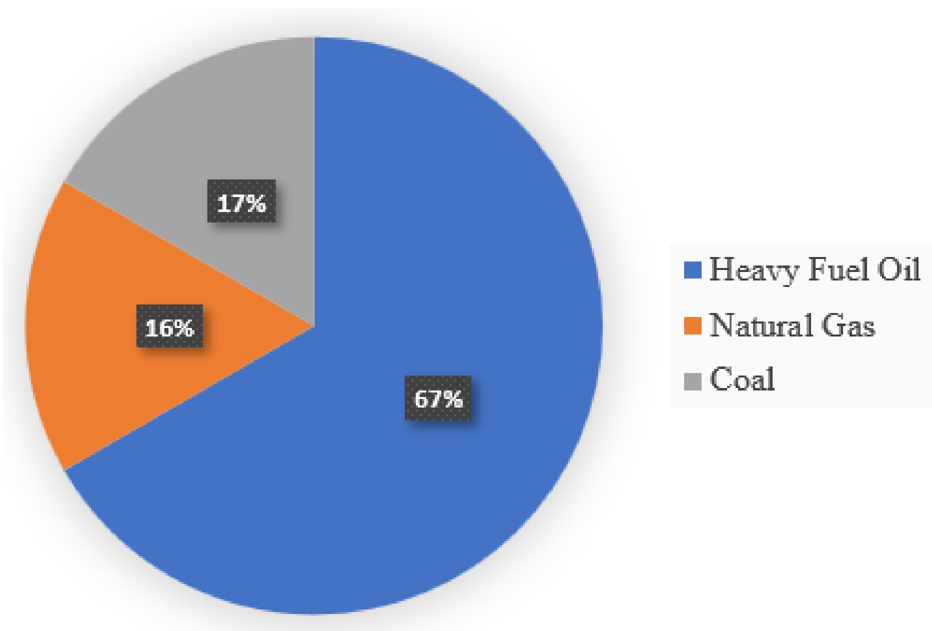


Appendix W.19 Views on the utilization pathways. Question: Can your current pipeline infrastructure be modified to transport CO_2 in the future?

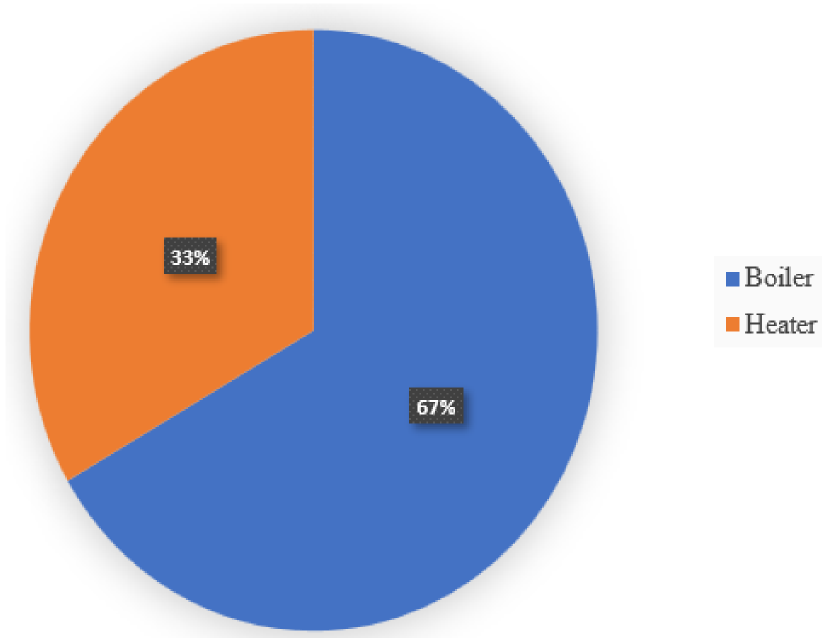
Appendix X. Information-Choice Questionnaires (ICQ) energy sector stakeholder results



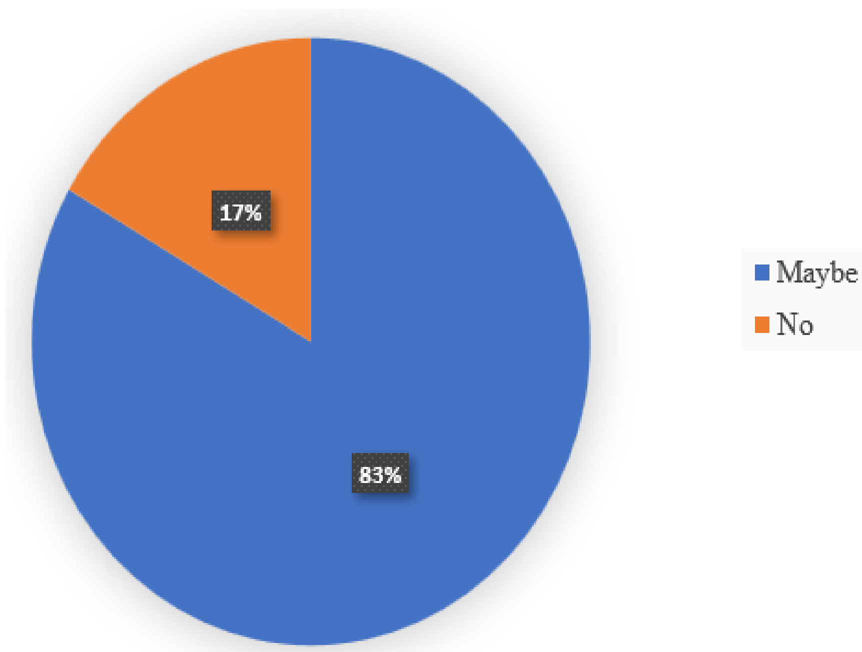
Appendix X.1 Views on basic information. Question: What are the advantages of your technology over other technologies in the market?



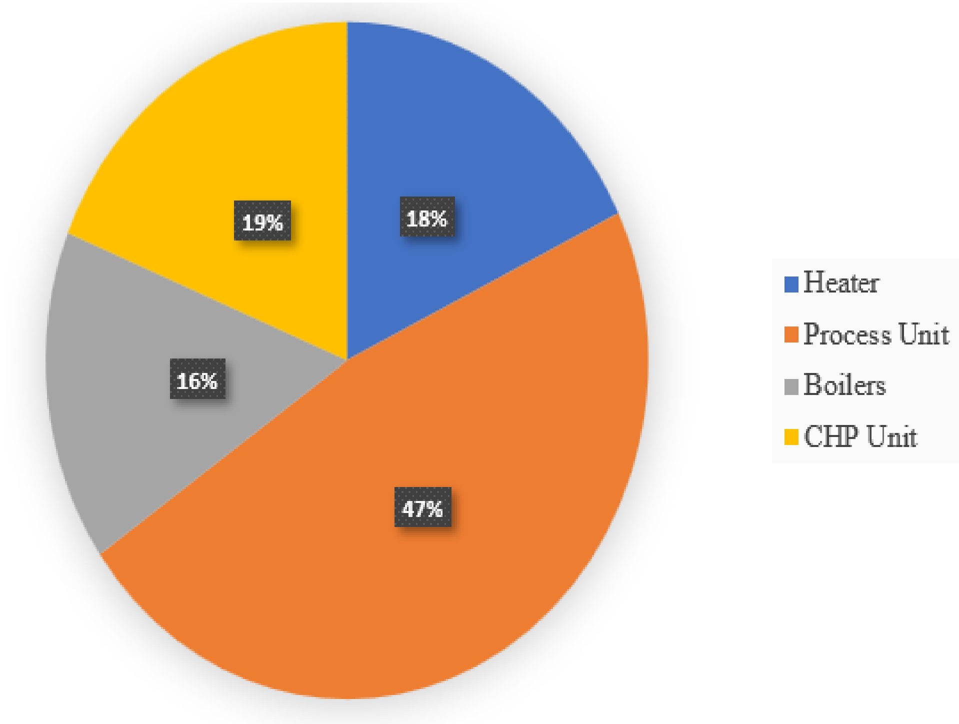
Appendix X.2 Views on basic information. Question: What is the type of fuel used in your facility?



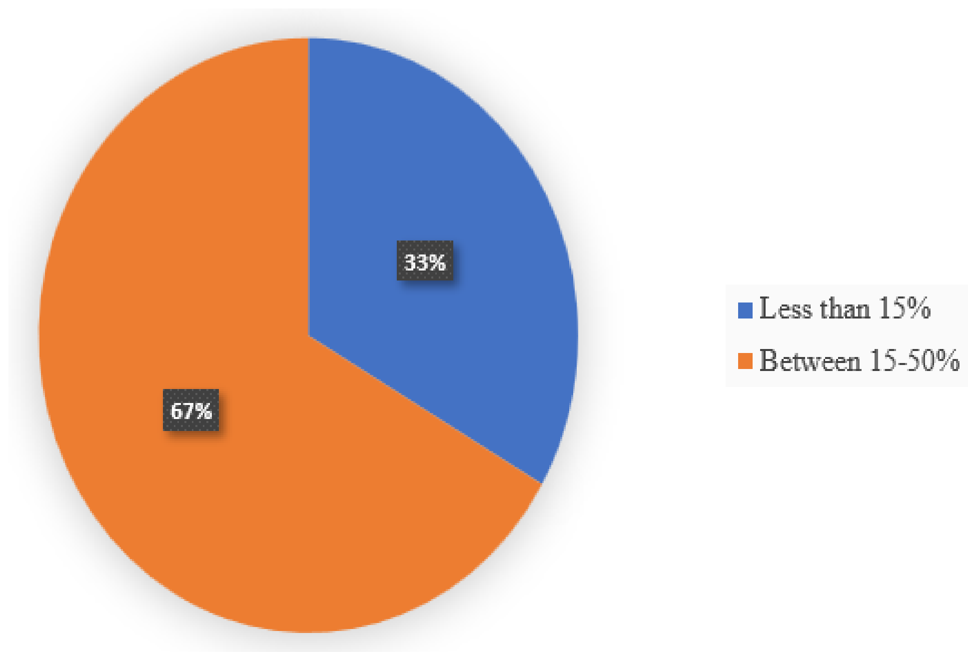
Appendix X.3 Views on basic information. Question: Which type of distributed energy system used in your facility?



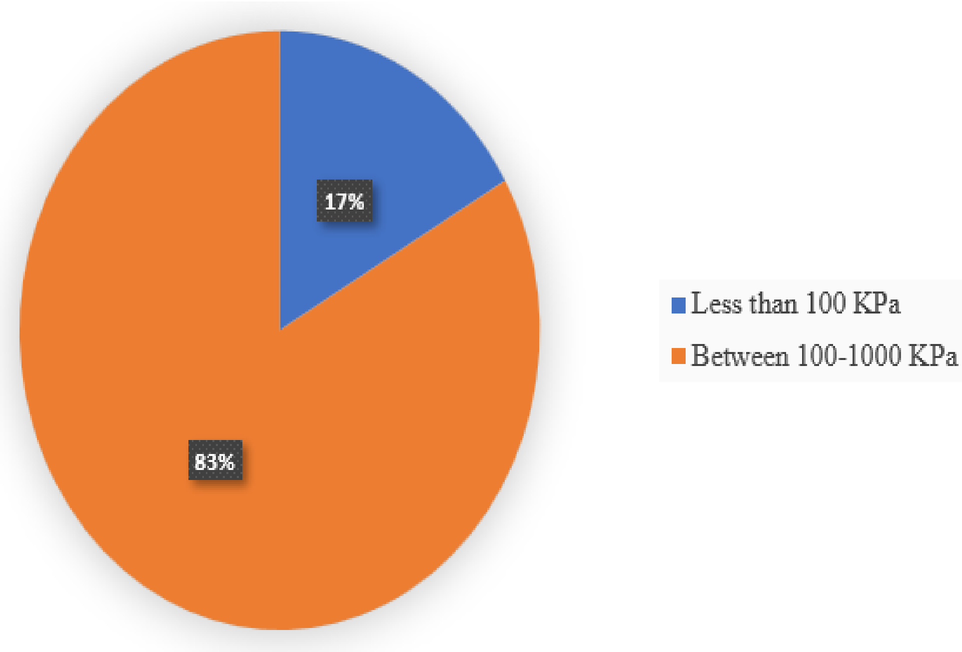
Appendix X.4 Views on basic information. Question: Can you allocate space for carbon-capturing facilities?



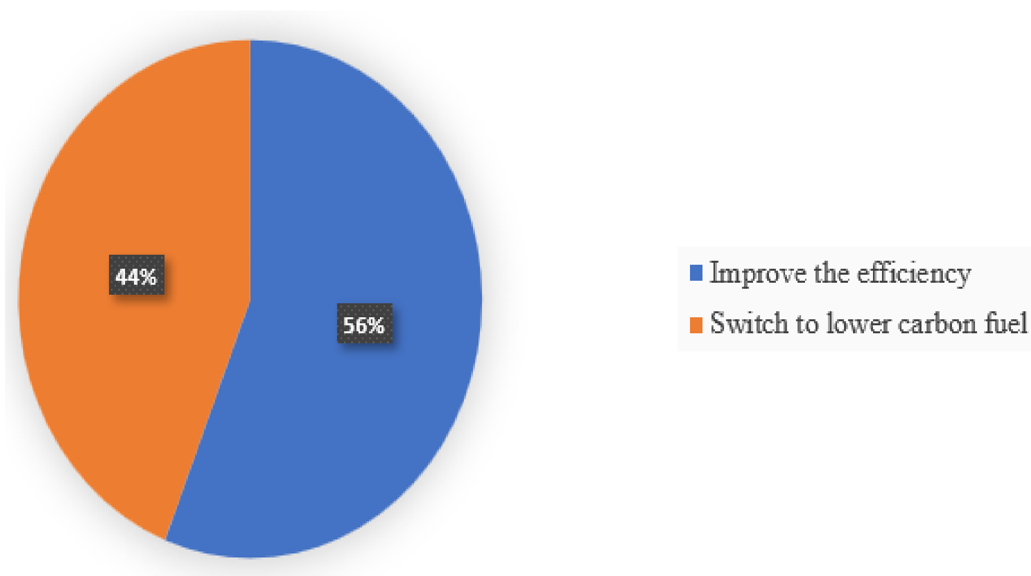
Appendix X.5 Views on the carbon footprint. Question: What are the main emission sources of CO_2 in your facility?



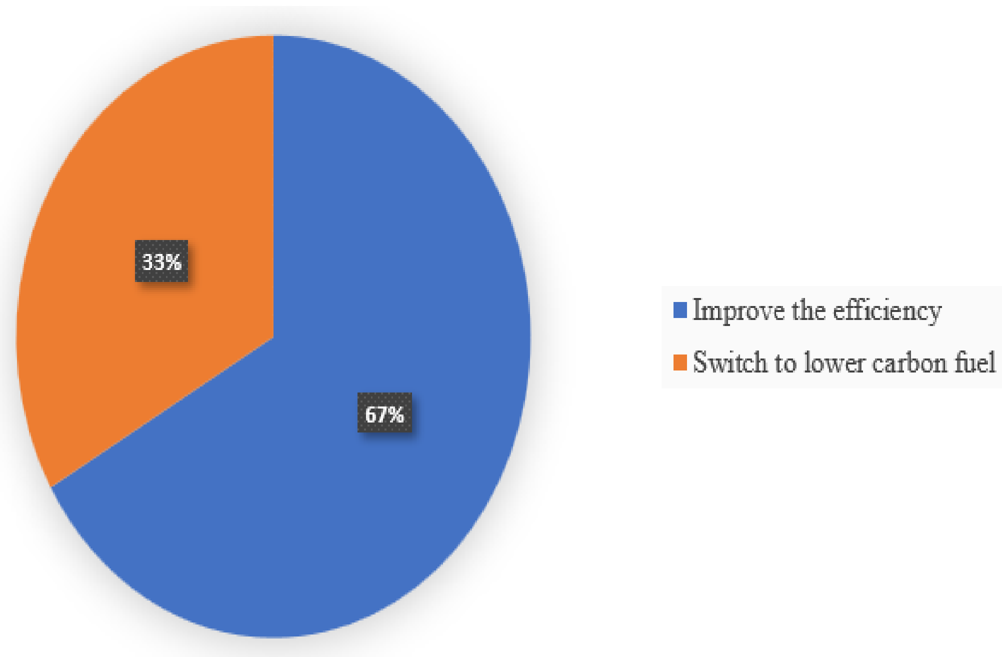
Appendix X.6 Views on the carbon footprint. Question: What is the concentration of CO_2 flow gas from these sources?



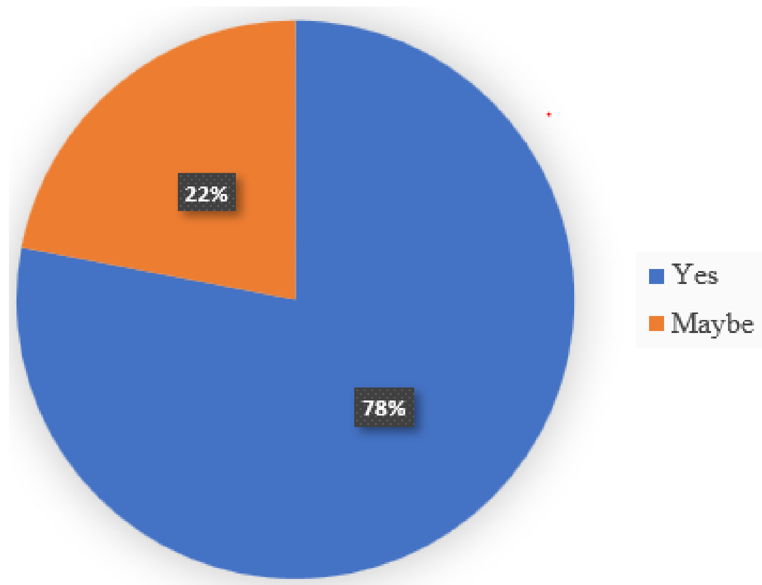
Appendix X.7 Views on the carbon footprint. Question: What the typical partial pressure in the flowing gas in your facility?



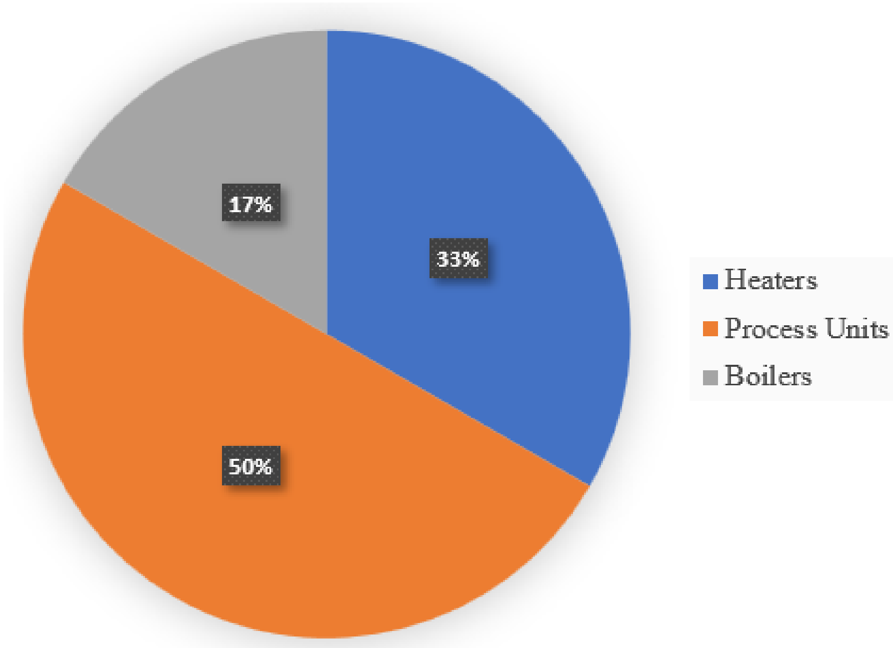
Appendix X.8 Views on carbon dioxide abatement practices Question: What is the current carbon abatement strategy utilised in your facility?



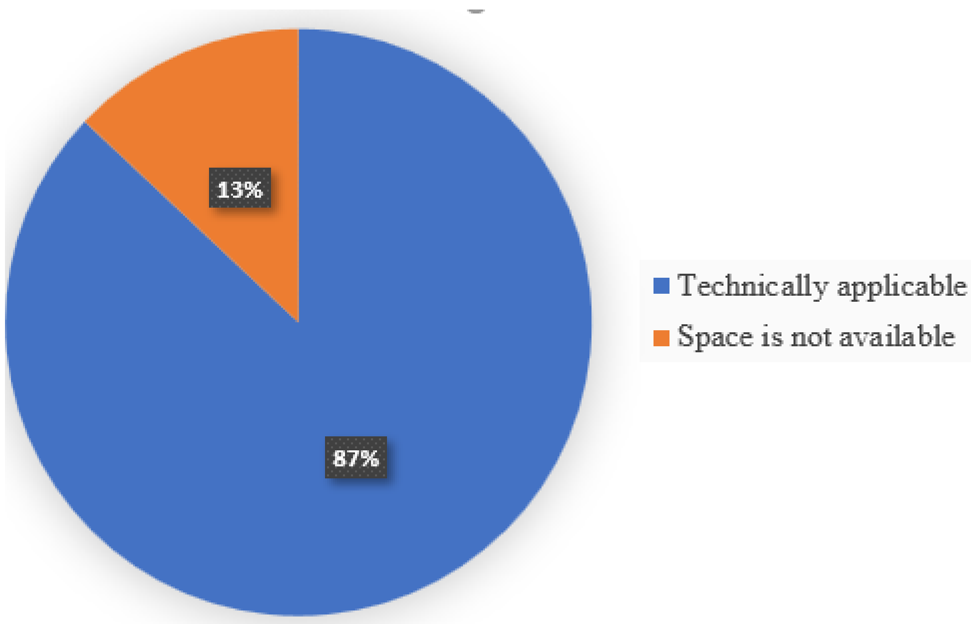
Appendix X.9 Views on carbon dioxide abatement practices Question: What is your long-term objective for carbon abatement?



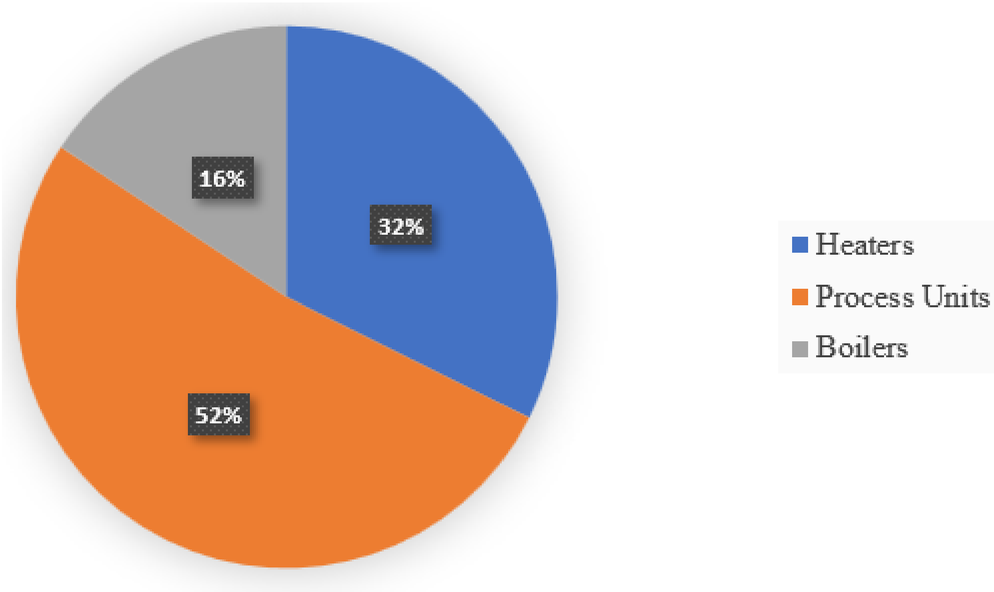
Appendix X.10 Views on carbon dioxide abatement practices. Question: If Kuwait Environmental Public Authority (KEPA) introduces a carbon tax, would you think of constructing a carbon capture unit?



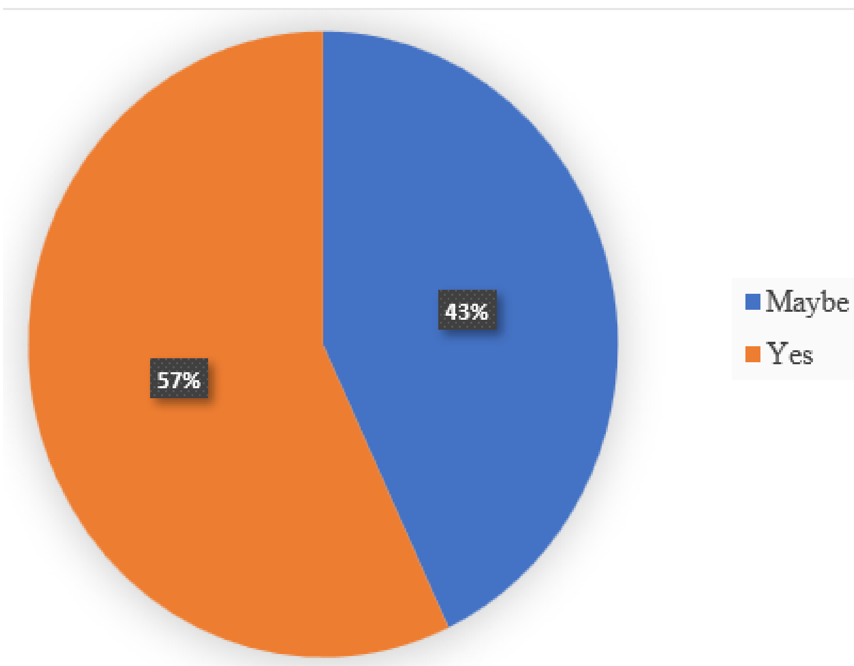
Appendix X.11 Views on post-combustion- if applicable. Question: Which units in your facility produce excess energy that can be reused in the capture unit?



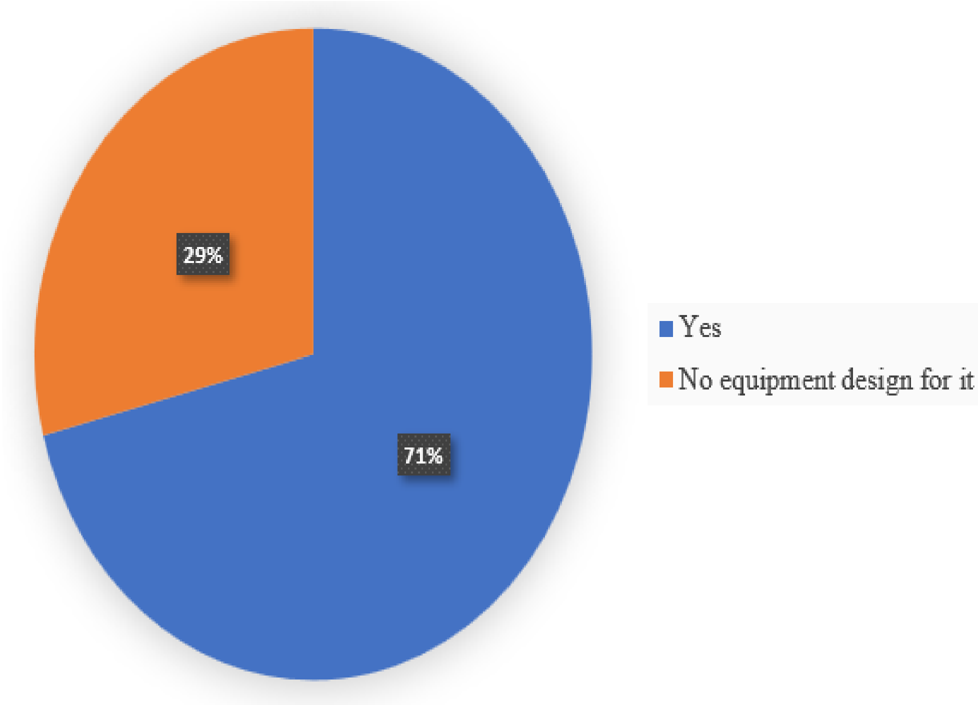
Appendix X.12 Views on oxy-fuel combustion- if applicable. Question: What are the technical and spatial constraints of deploying the Air Separation Unit (ASU) in your facility?



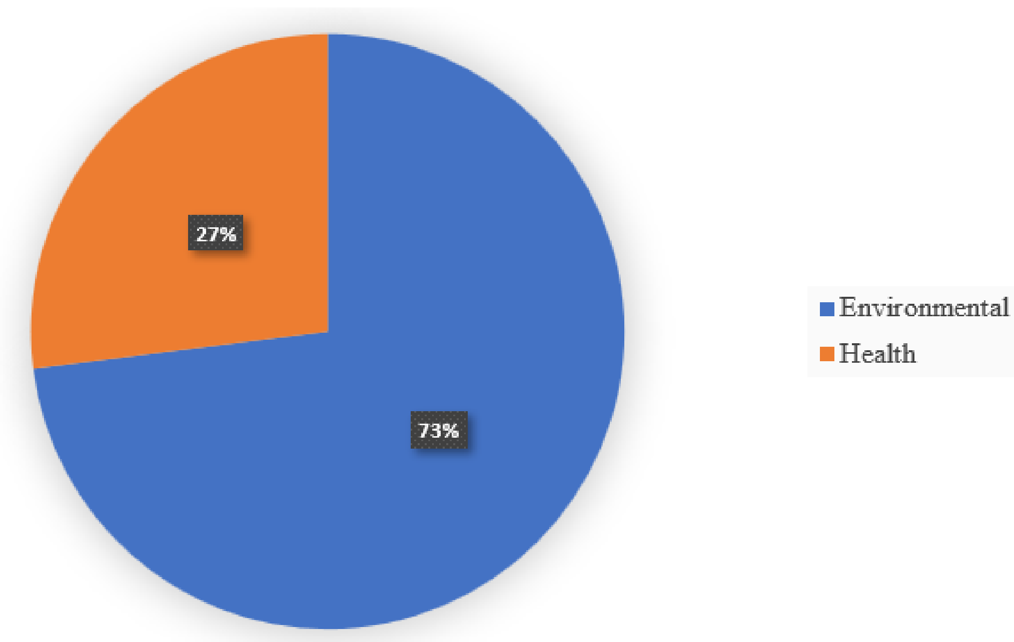
Appendix X.13 Views on oxy-fuel combustion- if applicable. Question: Which units in your facility need to be modified to work on full-oxy fuel combustion mode?



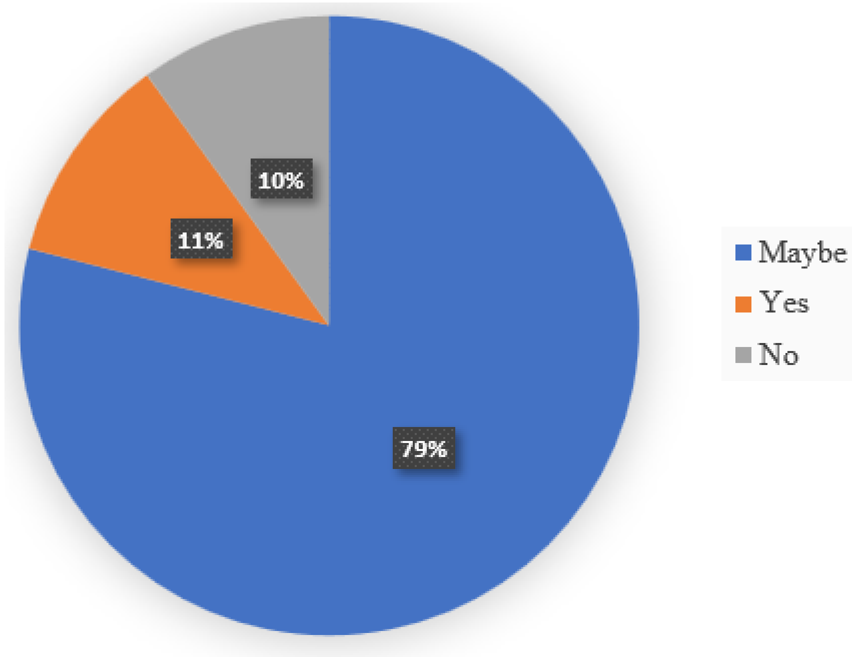
Appendix X.14 Views on oxy-fuel combustion- if applicable. Question: From a technical perspective, can you recycle back the CO_2 to the generator to reduce the combustion temperature?



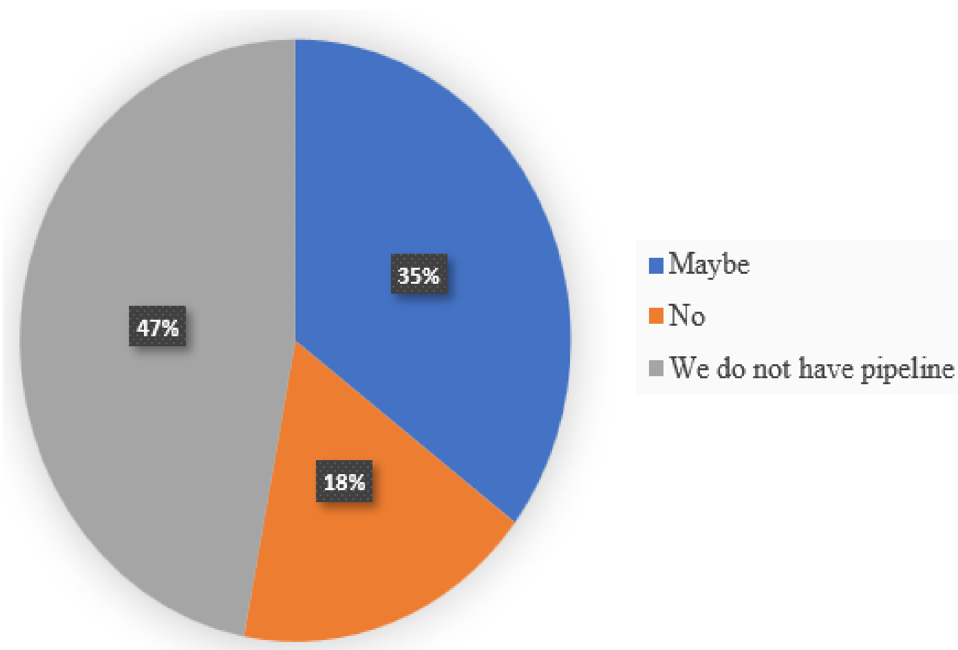
Appendix X.15 Views on pre-combustion - if applicable. Question: Can hydrogen be used as the primary fuel in your utilities? If no, what are the technical barriers?



Appendix X.16 Views on the risks associated with deploying carbon capture technologies. Question: In your opinion, what are the potential risks associated with deploying carbon capture technologies in your facility?

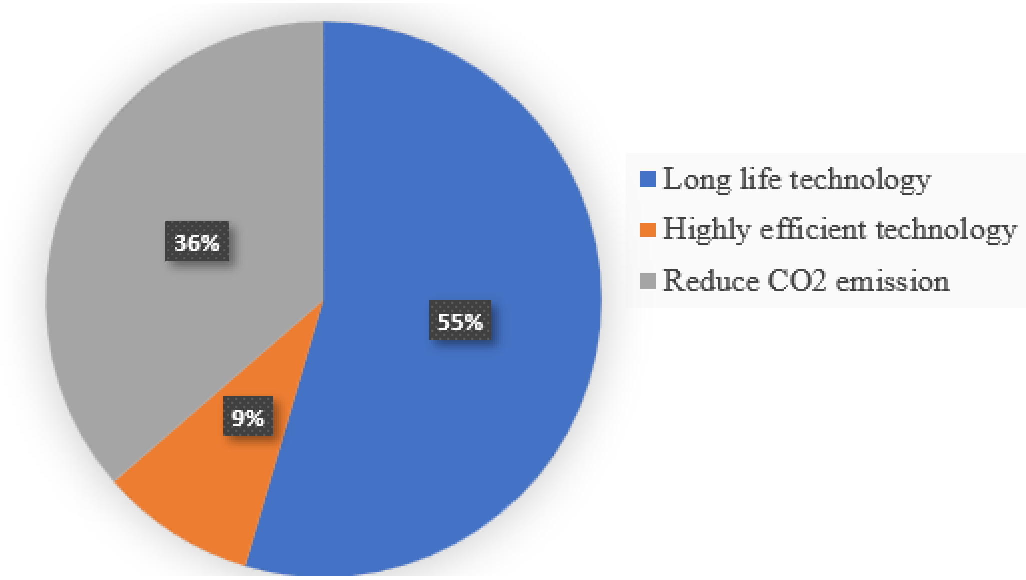


Appendix X.17 Views on the utilization pathways. Question: Can you utilize the captured CO_2 from your production pathway?

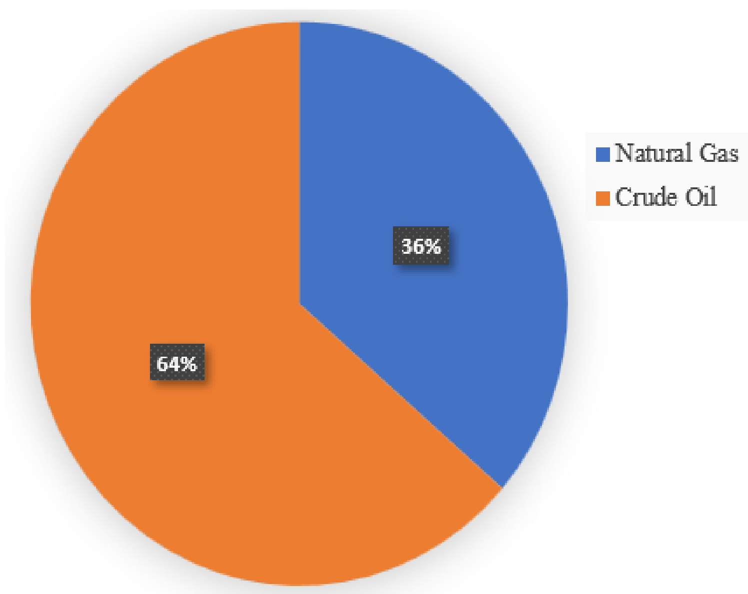


Appendix X.18 Views on the utilization pathways. Question: Can your current pipeline infrastructure be modified to transport CO_2 in the future?

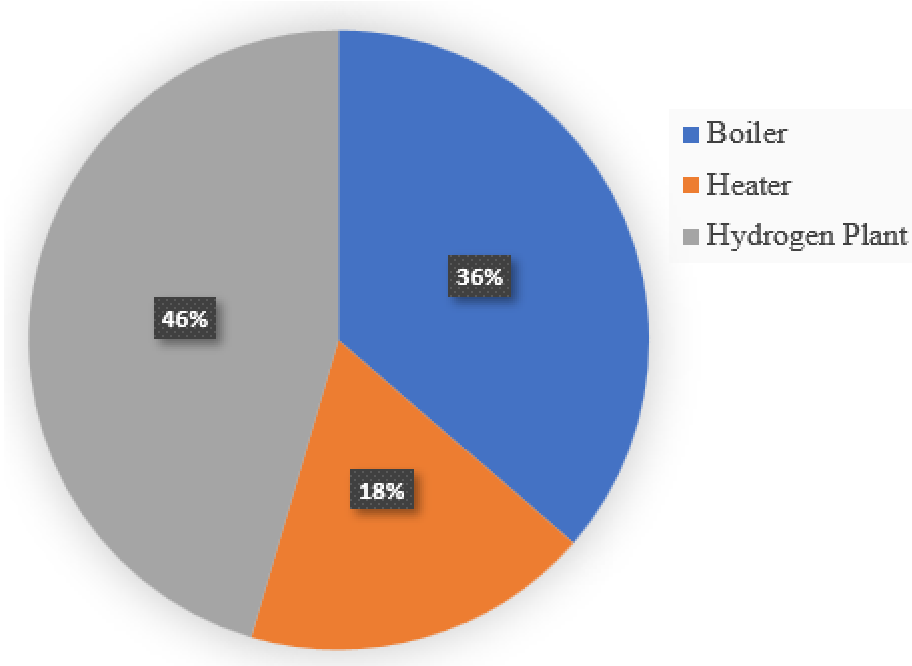
Appendix Y. Information-Choice Questionnaires (ICQ) refineries stakeholder results



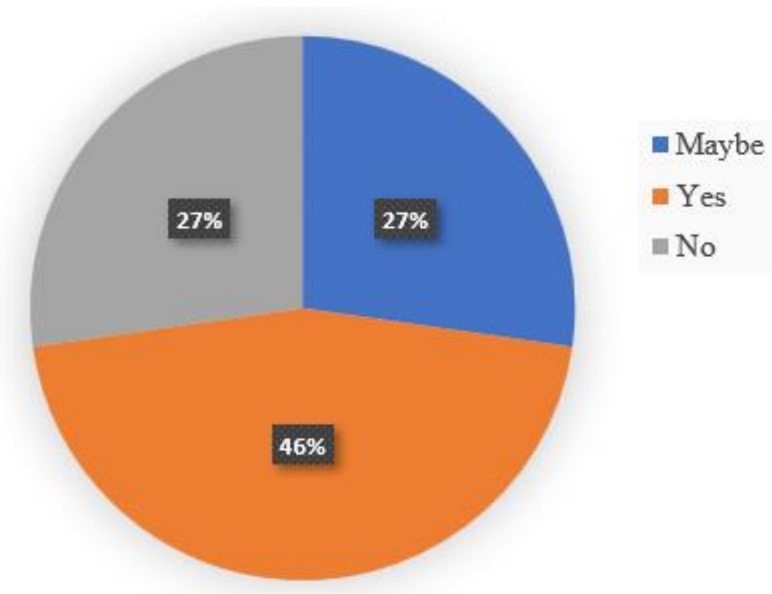
Appendix Y.1 Views on basic information. Question: What are the advantages of your technology over other technologies in the market?



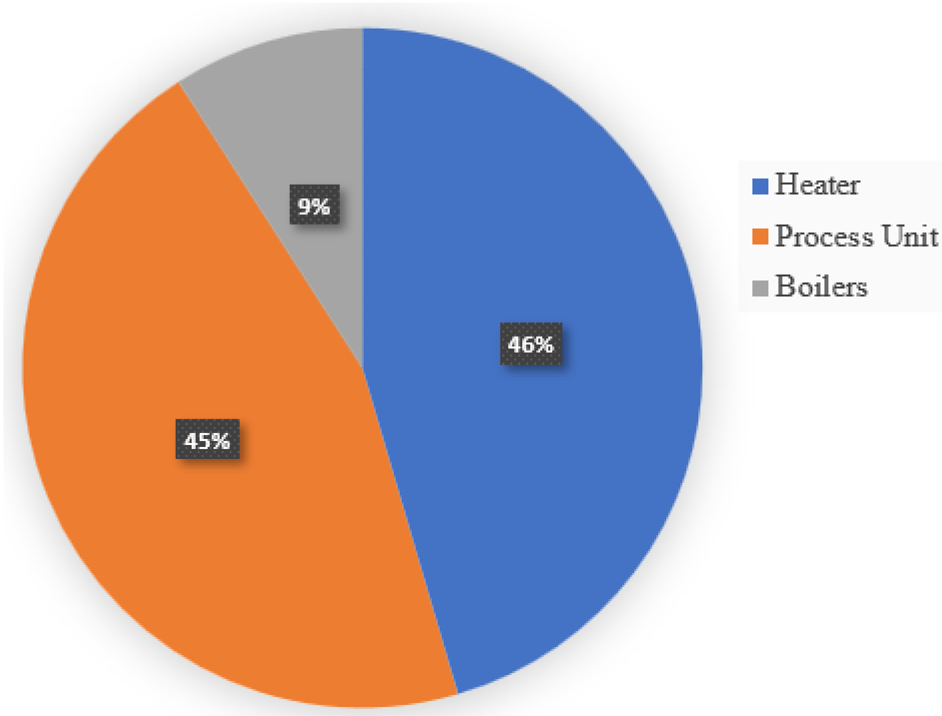
Appendix Y.2 Views on basic information. Question: What is the type of fuel used in your facility?



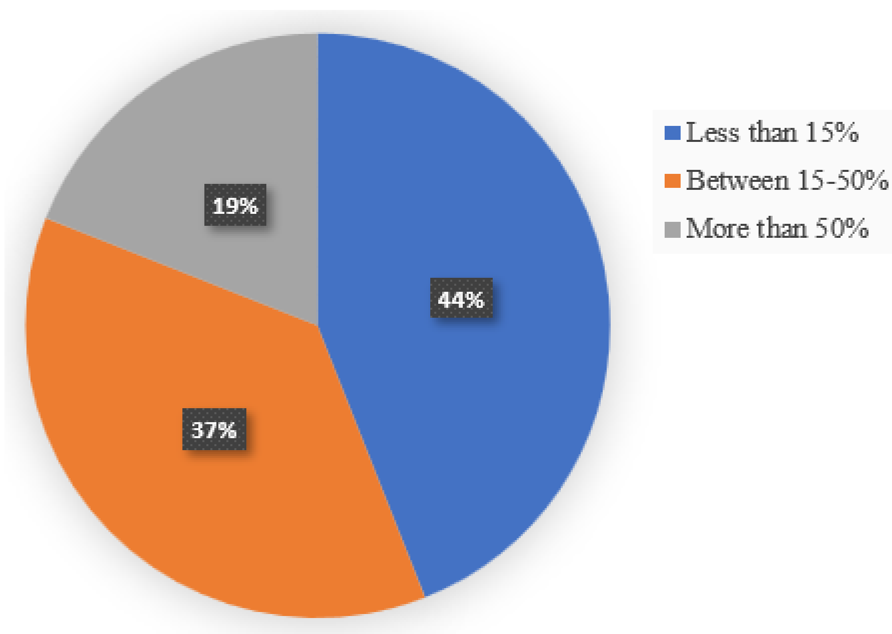
Appendix Y.3 Views on basic information. Question: Which type of distributed energy system used in your facility?



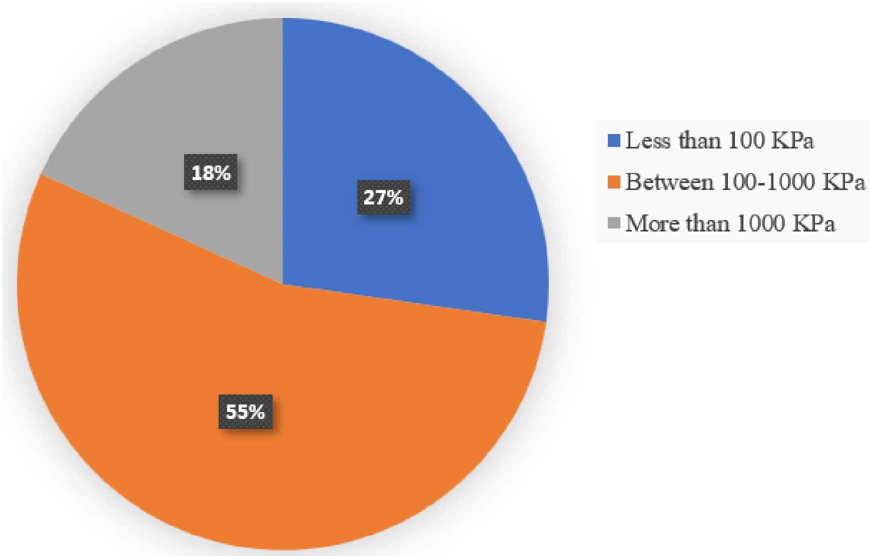
Appendix Y.4 Views on basic information. Question: Can you allocate space for carbon-capturing facilities?



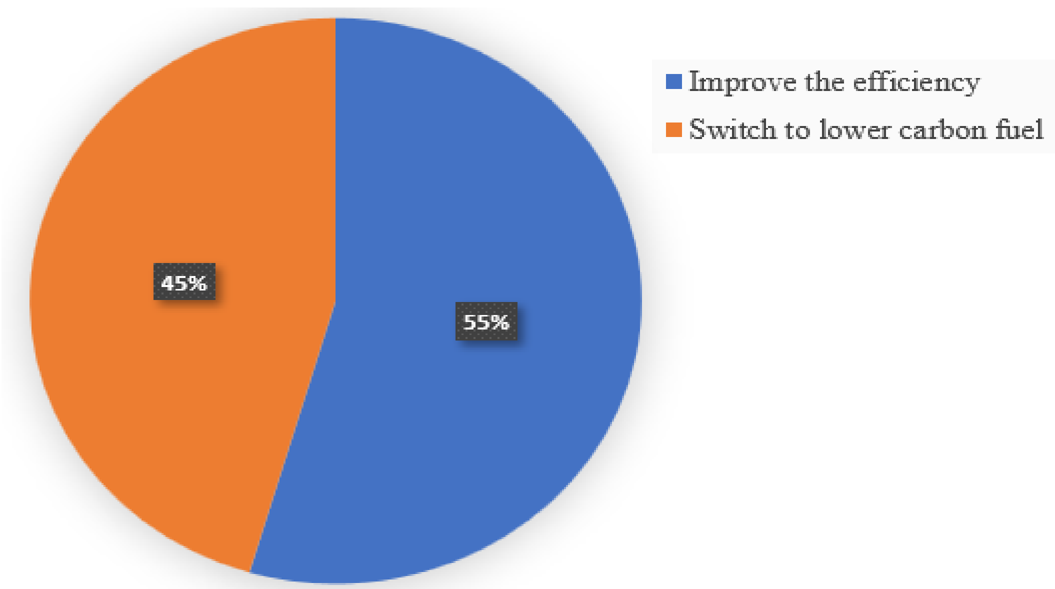
Appendix Y.5 Views on the carbon footprint. Question: What are the main emission sources of CO_2 in your facility?



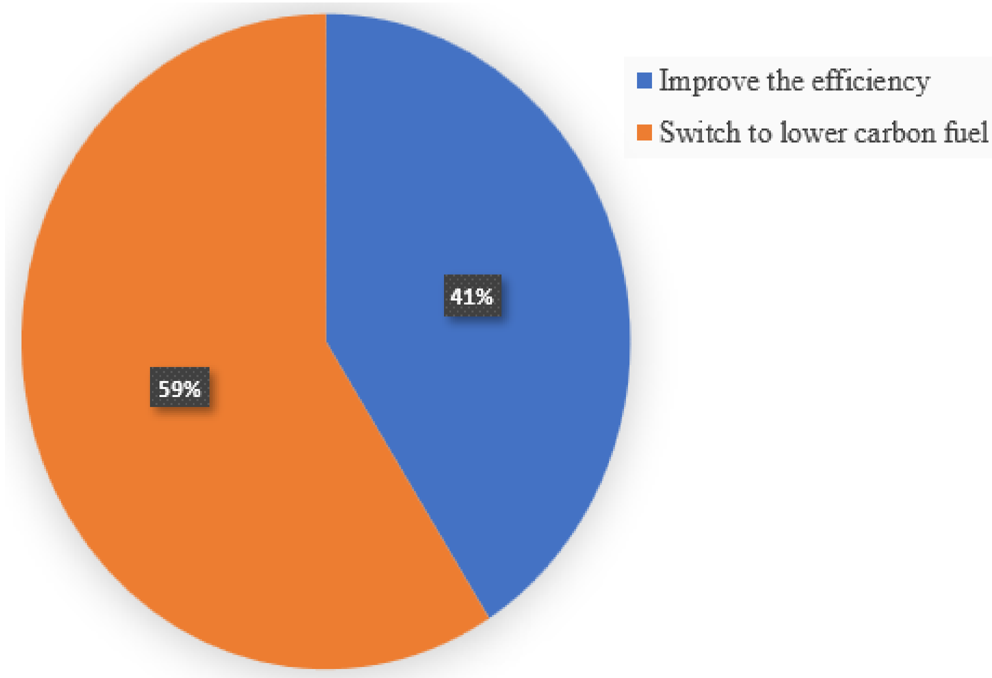
Appendix Y.6 Views on the carbon footprint. Question: What is the concentration of CO_2 flow gas from these sources?



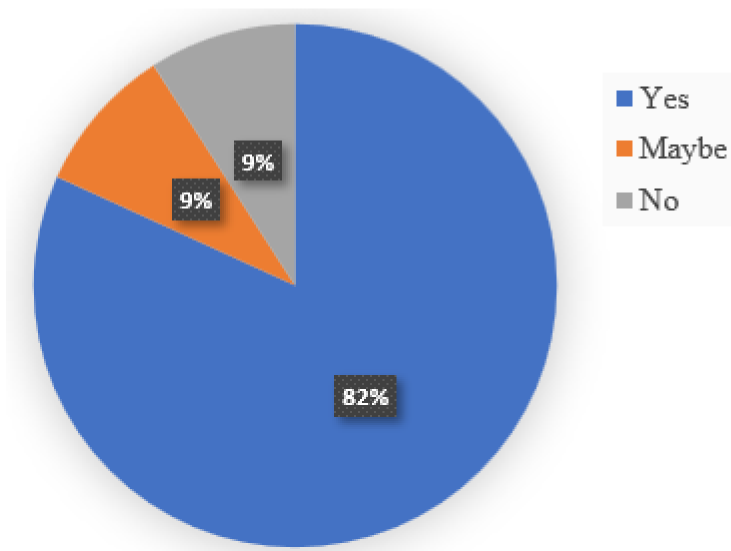
Appendix Y.7 Views on the carbon footprint. Question: What the typical partial pressure in the flowing gas in your facility?



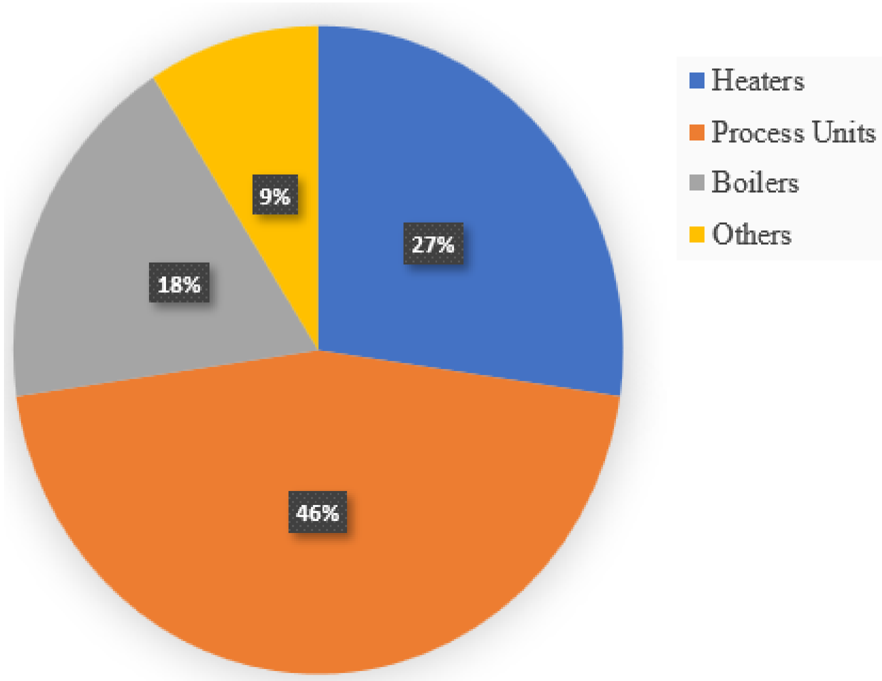
Appendix Y.8 Views on carbon dioxide abatement practices Question: What is the current carbon abatement strategy utilised in your facility?



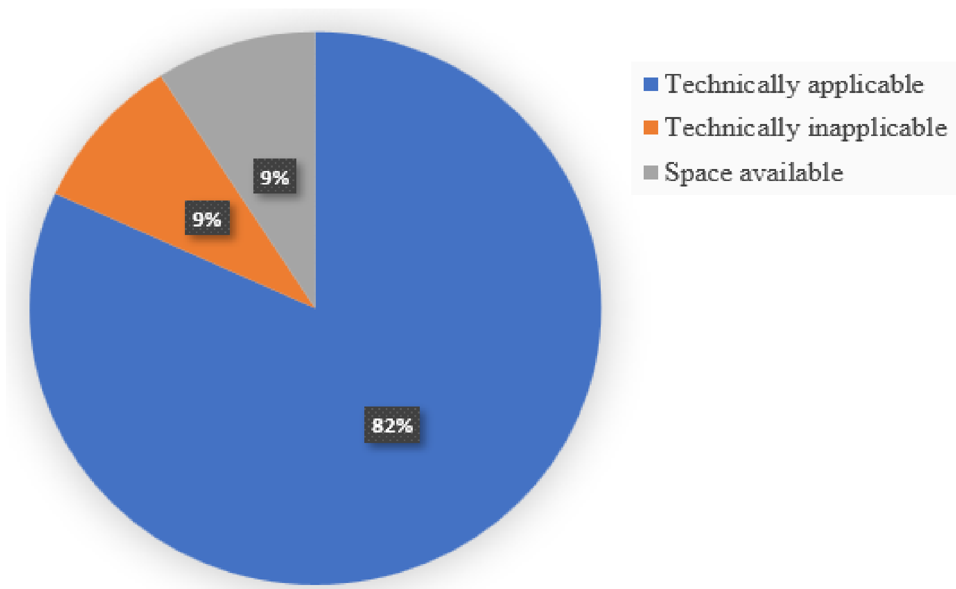
Appendix Y.9 Views on carbon dioxide abatement practices Question: What is your long-term objective for carbon abatement?



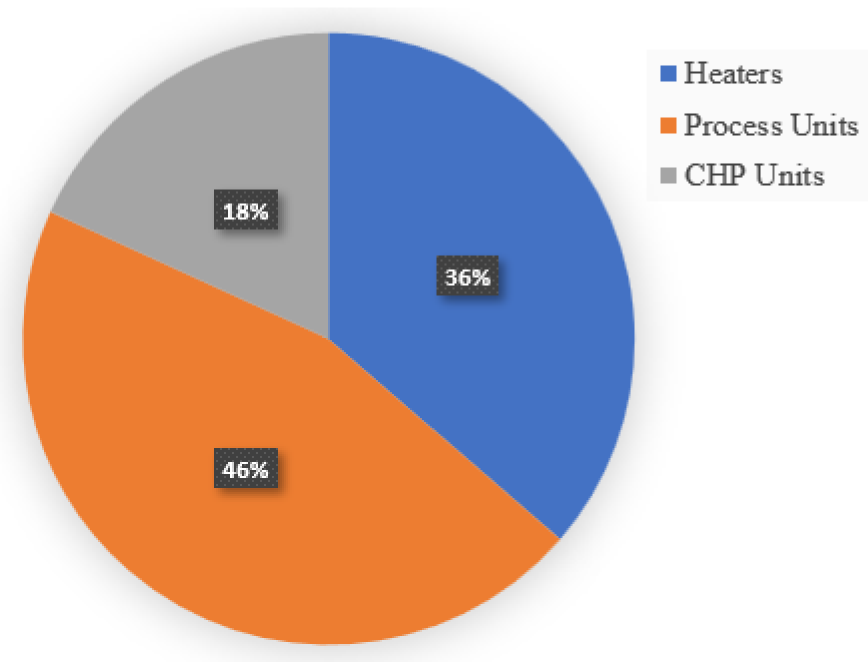
Appendix Y. 10 Views on carbon dioxide abatement practices. Question: If Kuwait Environmental Public Authority (KEPA) introduces a carbon tax, would you think of constructing a carbon capture unit?



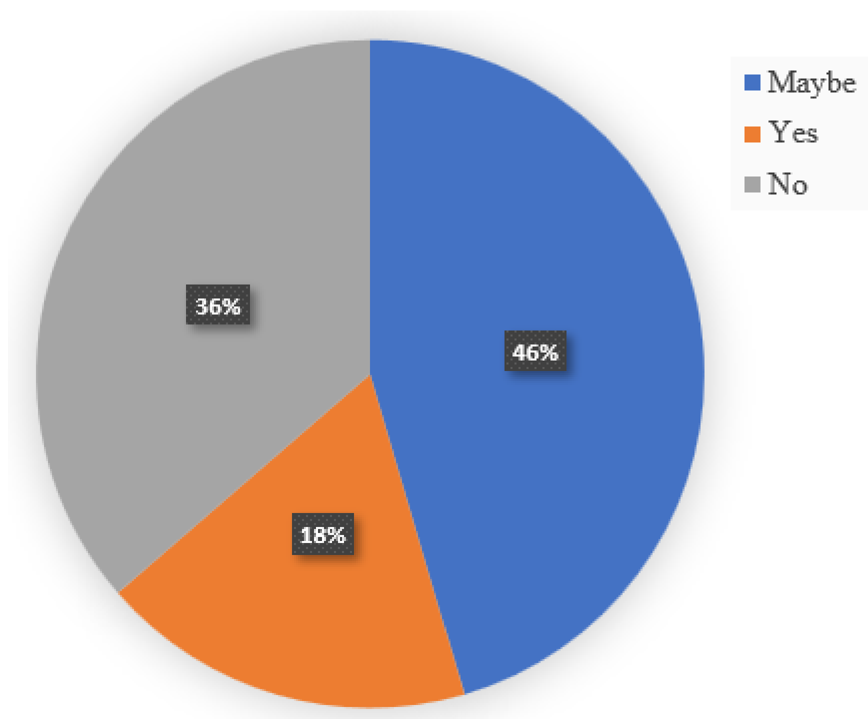
Appendix Y.11 Views on post-combustion- if applicable. Question: Which units in your facility produce excess energy that can be reused in the capture unit?



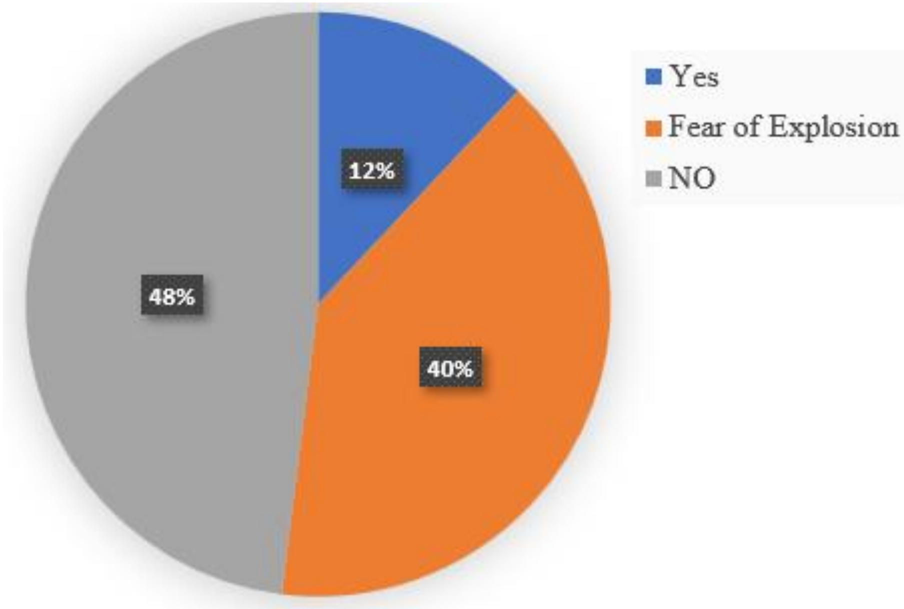
Appendix Y.12 Views on oxy-fuel combustion- if applicable. Question: What are the technical and spatial constraints of deploying the Air Separation Unit (ASU) in your facility?



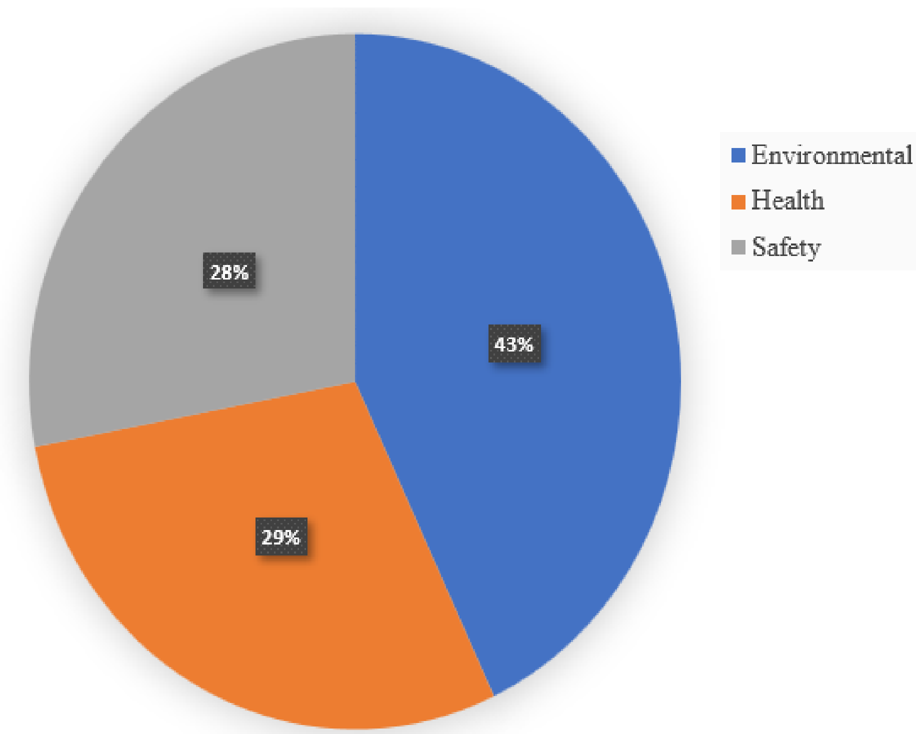
Appendix Y.13 Views on oxy-fuel combustion- if applicable. Question: Which units in your facility need to be modified to work on full-oxy fuel combustion mode?



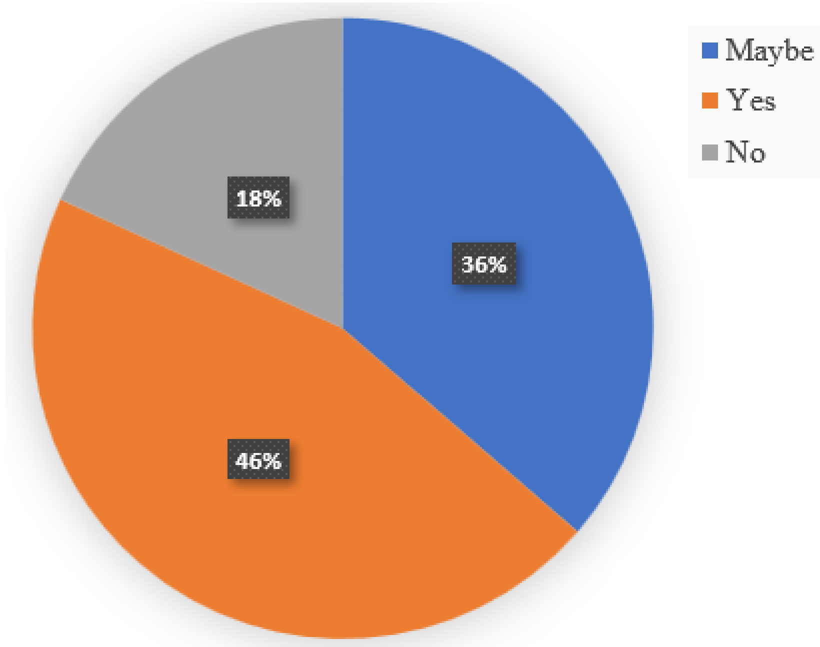
Appendix Y.14 Views on oxy-fuel combustion- if applicable. Question: From a technical perspective, can you recycle back the CO_2 to the generator to reduce the combustion temperature?



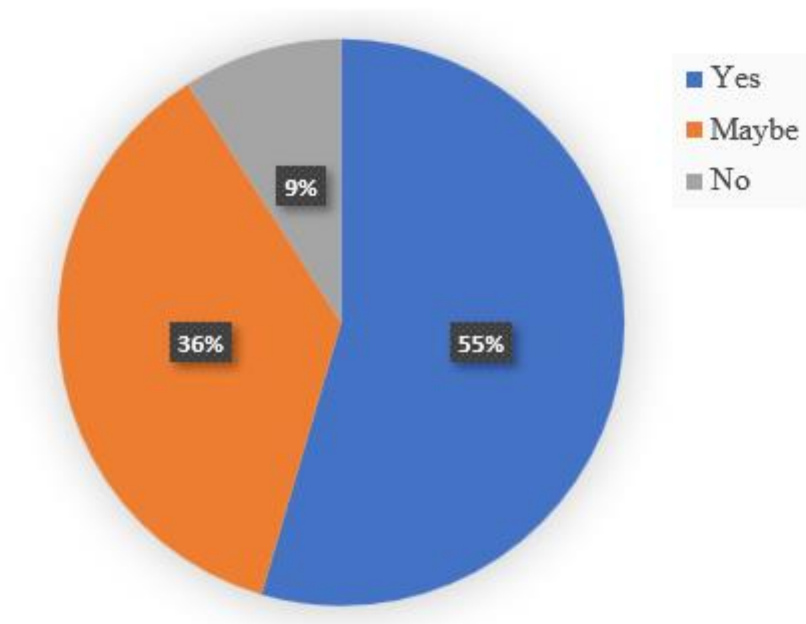
Appendix Y.15 Views on pre-combustion - if applicable. Question: Can hydrogen be used as the primary fuel in your utilities? If no, what are the technical barriers?



Appendix Y.16 Views on the risks associated with deploying carbon capture technologies. Question: In your opinion, what are the potential risks associated with deploying carbon capture technologies in your facility?



Appendix Y.17 Views on the utilization pathways. Question: Can you utilize the captured CO_2 from your production pathway?



Appendix Y.18 Views on the utilization pathways. Question: Can your current pipeline infrastructure be modified to transport CO_2 in the future?

Appendix Z. Java model

```
{
                        n: 'nil',
                           h: 0.00001,
                    w: 0.00001
             },


      {
           n: 'Fertilisers',              h: 25.25,          w: 6.943          },
      {
           n: 'hydrogen production',         h: 34.44,          w: 7.37           },
      {
                   n: 'Cement',                  h: 53.9,           w: 0.322          },
      {
                   n: 'Iron and Steel',            h: 64.3 ,          w: 0.312          },
      {
                   n: 'Paper production',          h: 66.25,          w: 1.04           },
      {
           n: 'Chemicals',                h: 75.433,          w: 12.417        },
      {
                   n: 'Downstream',               h: 75.433,          w: 8.962         },
      {
                   n: 'Aluminium',                h: 75.433,           w: 0.167        },
      {
                   n: 'Upstream',                 h: 75.433,           w: 0.255        },
      {
            n: 'Cement',                    h: 77.61,            w: 0.322        },
      {
                   n: 'Petrochemicals',            h: 83.43,          w: 2.64           },
      {
```

n: 'Chemicals', h: 84.5, w: 12.417 },
{
n: 'Downstream', h: 84.5, w: 8.962 },
{
n: 'Aluminium', h: 84.5, w: 0.167 },
{
n: 'Upstream', h: 84.5, w: 0.255 },
{
n: 'Chemicals', h: 88.34, w: 2.033 },
{
n: 'Iron and Steel', h: 105.8 , w: 0.312 },
{
n: 'Cement', h: 132.38, w: 0.322 },
{
n: 'Powerstations', h: 163.38, w: 41.63 },

]

Appendix AA. Cost estimation for post- and oxy-combustion technologies

Appendix AA.1 Cost estimation for post-combustion technologies

Sector	CO_2 (Mt)	CO_2 (t)	Type of the capture process	Cost to capture per t (USD)	Capture process eff. [-]	CO_2 captured (t)	CO_2 captured (Mt)	CO_2 saving (%)	Cumulative CO_2	Total cost (USD)	Total cost (USDm)	Cumulative cost (USDm)
Chemicals	25.45	25450000	Post-combustion	84.50416499	0.5	12725000.00	12.73	15.75	13.94	1075315499.52	1075.32	1028.88
Petrochemical	2.64	2640000	Post-combustion	84.50416499	0.5	1320000.00	1.32	1.63	15.57	111545497.79	111.55	1140.43
Downstream	8.962	8962000	Post-combustion	84.50416499	0.5	4481000	4.481	5.546519717	21.12	378663163.3	378.6631633	1519.09
Iron and steel industry	0.312	312000	Post-combustion	105.8024294	0.5	156000	0.156	0.193094639	21.31	16505178.99	16.50517899	1535.59
Cement industry	0.322	322000	Post-combustion	132.3822041	0.5	161000	0.161	0.199283569	21.51	21313534.86	21.31353486	1556.91
Paper production	1.0454	1045400	Post-combustion	66.24850978	0.5	522700	0.5227	0.646990818	22.16	34628096.06	34.62809606	1591.54
Upstream	0.255	255000	Post-combustion	84.50416499	0.5	127500	0.1275	0.157817734	22.32	10774281.04	10.77428104	1602.31
Power stations	41.636	41636000	Post-combustion	163.3803426	0.5	20818000	20.818	25.76823197	48.09	3401251972	3401.251972	5003.56
Aluminium industry	0.167	167000	Post-combustion	84.50416499	0.5	83500	0.0835	0.103355143	48.19	7056097.777	7.056097777	5010.62
Total	80.7894						40.39	50.00			5057.05	

Appendix AA.2 Cost estimation for oxy-combustion technologies

Sector	Carbon emission (Mt)	Carbon emission (t)	Type of the capture process	Cost to capture per metric ton (USD)	Capture process eff. [-]	CO_2 captured (t)	CO_2 captured (Mt)	CO2 saving (%)	Cumulative CO_2	Total cost (USD)	Total cost (USDm)	Cumulative cost (USDm)
Chemicals	25.45	25450000	Oxy combustion	75.43374511	0.5	1.3E+07	12.725	15.7508287	13.94098653	959894406.5	959.8944065	918.4435636
Petrochemical	2.64	2640000	Oxy combustion	75.43374511	0.5	1320000	1.32	1.633877712	15.57486425	99572543.54	99.57254354	1018.016107
Downstream	8.962	8962000	Oxy combustion	75.43374511	0.5	4481000	4.481	5.546519717	21.12138396	338018611.8	338.0186118	1356.034719
Iron and steel industry	0.312	312000	Oxy combustion	64.29664728	0.41	127920	0.12792	0.158337604	21.27972157	8224827.12	8.22482712	1364.259546
Cement industry	0.322	322000	Oxy combustion	53.90584981	0.73	235060	0.23506	0.290954011	21.57067558	12671109.06	12.67110906	1376.930655
Paper production	1.0454	1045400	Oxy combustion	66.24850978	0.5	522700	0.5227	0.646990818	22.2176664	34628096.06	34.62809606	1411.558751
Upstream	0.255	255000	Oxy combustion	75.43374511	0.5	127500	0.1275	0.00001275	22.21767915	9617802.501	9.617802501	1421.176554
Power stations	41.636	41636000	Oxy combustion	163.3803426	0.5	2.1E+07	20.818	25.76823197	47.98591112	3401251972	3401.251972	4822.428526
Aluminium industry	0.167	167000	Oxy combustion	75.43374511	0.5	83500	0.0835	0.103355143	48.08926626	6298717.717	6.298717717	4828.727244
Total	80.7894								233.9981548			18517.57567