# Petroleum Supply Chain Planning under Environmental Regulations: A Case Study in Libya

by

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**FOREWORD**

This thesis produced the following peer-reviewed journal and conference papers.

a) Supply Chain Planning in the Petroleum Industry: The Libyan Petroleum Sector Case Study. *International Conference on Modeling, Optimization, and Simulation – MOSIM 2020, 12-14 Nov 2020, AGADIR, Maroc* https://hal.archives-ouvertes.fr/hal-03177502/document

b) Recent advances and opportunities in planning green petroleum supply chains: a model-oriented review. *International Journal of Sustainable Development & World Ecology, 1-16* https://www.tandfonline.com/doi/pdf/10.1080/13504509.2020.1862935

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**Planification de la chaîne d'approvisionnement pétrolière sous les contraintes de réglementation environnementale : une étude de cas en Libye**

Otman ABDUSSALAM


## RÉSUMÉ

Aujourd'hui, les sociétés pétrolières ne peuvent être compétitives et efficaces sans considérer les solutions potentielles fournies par les modèles d'optimisation de la gestion durable de la chaîne d'approvisionnement (SSCM). SSCM peut résoudre différents défis auxquels ce secteur est confronté. Les universitaires et les praticiens examinent les opportunités offertes par les outils de prise de décision pour planifier des chaînes d'approvisionnement pétrolières durables. Par conséquent, l'objectif principal de cette étude est de comprendre l'évolution de la planification durable de la chaîne d'approvisionnement dans l'industrie pétrolière et de mettre en évidence les spécificités du corpus de connaissances dans ce domaine. Par conséquent, il est nécessaire de développer un modèle mathématique pour la planification et l'optimisation des chaînes d'approvisionnement pétrolières du point de vue national, en considérant l'aspect économique comme une première étape.

Le modèle est présenté pour identifier les décisions liées au flux entre les nœuds, les capacités de production à chaque niveau, et comment satisfaire la demande pour maximiser le profit des marchés locaux et internationaux. De plus, dans un deuxième temps, un nouveau modèle de programmation linéaire à nombres entiers mixtes est présenté basé sur les dimensions économique et environnementale pour évaluer l'impact de l'introduction d'une réglementation environnementale stricte limitant les émissions de gaz à effet de serre. L'objectif de ce modèle est de minimiser le coût total des secteurs du brut, de la raffinerie et de la pétrochimie pour se conformer aux normes et réglementations environnementales et également d'examiner l'impact de l'intégration des décisions d'investissement dans différentes options de réduction des émissions de carbone.

Les résultats de calcul basés sur l'industrie pétrolière libyenne sont analysés et démontrent les capacités du modèle pour faire face au compromis entre le coût total et les problèmes environnementaux du secteur pétrolier. Une analyse de sensibilité est réalisée sur certains paramètres pour évaluer les performances de la chaîne d'approvisionnement et concevoir un plan d'atténuation pour gérer les risques environnementaux. Cela permettra aux chercheurs et aux praticiens de mieux comprendre comment évaluer les performances de la chaîne d'approvisionnement afin d'atteindre les objectifs de durabilité.


**Mots-clés**: chaîne d'approvisionnement durable, planification, modélisation mathématique, pétrole brut, pétrole, gestion de la chaîne d'approvisionnement verte, incertitude, optimisation multiobjectifs.

**Petroleum Supply Chain Planning under Environmental Regulations:**
**A Case Study in Libya**

Otman ABDUSSALAM

## ABSTRACT

Today, petroleum companies cannot be competitive and efficient without considering potential solutions provided by sustainable supply chain management (SSCM) optimization models. SSCM can solve different challenges faced by this sector. Academics and practitioners consider the opportunities offered by decision-making tools for planning sustainable petroleum supply chains. Therefore, the primary objective of this study is to understand the evolution of sustainable supply chain planning in the petroleum industry and how to develop a data-driven decision-making tool to assess different transformation plans for the petroleum sector under the uncertainty of environmental regulations

This study aims first to understand the evolution of sustainable supply chain planning in the petroleum industry and highlight the specificities of the body of knowledge in this area and develop a general framework. A mathematical model for planning and optimizing the petroleum supply chains from the country-level perspective considers the economic side. A deterministic mathematical model is presented to identify the decisions related to the flow between nodes, production capacities at each level, and how to satisfy the demand to maximize the profit from local and international markets. The developed model was solved by using commercial software. Furthermore, the Libyan petroleum case study is applied as an example to show possible improvements in the petroleum supply chain application, visualize the new supply chain configuration, and validate the results. Results show that the model allows improvements in both profit and service level if suitable production and distribution decisions are set. Finally, the optimization model helps decision-makers identify the production and distribution plan under some risky events.

Introduction of new environmental regulations to decarbonize the petroleum sector, also, prepare a transformation plan (strategic decisions) for the petroleum sector. The objective is to minimize the crude, refinery, and petrochemical sectors total cost and meet environmental standards and regulations. It presents a deterministic mathematical programming model for planning the supply chain. Furthermore, the study examines the impact of incorporating investment decisions through different carbon emission reduction options and evaluating the supply chain performance based on the economic and environmental dimensions.

A data-driven and generic decision-making model for eco-efficient supply chain planning is presented to evaluate the impact of introducing a stringent environmental regulation limiting greenhouse gas emissions. Experimental results based on the Libyan petroleum industry are analyzed and demonstrate model capabilities to deal with the trade-off between the total cost and the petroleum sector's environmental issues. A sensitivity analysis is carried out on some parameters to design a mitigation plan to manage the environmental risks. This study shows that it's possible to achieve up to 32% carbon emission reduction if the carbon capture and storage projects are implemented in the different petroleum sectors. However, suppose the cumulative carbon reduction objective is more than 32 % for the next 20 years. In that case, it

will be necessary to implement green (solar) energies to be used in the extraction, refineries, and petrochemical plants.

**Keywords**: sustainable supply chain, planning, mathematical modelling, crude oil, petroleum, green supply chain management, uncertainty, multiobjective optimization

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| | |
|---|---|
| BARON | Branch-And-Reduce Optimization Navigator |
| SBB | Simple Branch and Bound |
| $CO_2$ | Carbon dioxide |
| $SO_2$ | Sulphur oxides |
| H2 | Hydrogen |
| VOC | Volatile Organic Compounds |
| SOx | Sulphur oxides |
| NOx | Nitrogen oxides |
| CCE | Journal of Computers & Chemical Engineering |
| JCP | Journal of Cleaner Production |
| AE | Journal of Applied Energy |
| EF | Journal of Energy & Fuels |
| PST | Journal of Petroleum Science and Technology |
| CCS | Carbon capture and storage |
| GHG | Greenhouse gas |
| GDP | Gross domestic product |
| MMbbl | One million barrels of crude oil |
| API | American Petroleum Institute gravity |

# INTRODUCTION

## Research context

The petroleum industry is a significant part of the world economy, specifically in the energy sector. This industry plays an essential role in our daily lives by supplying transportation needs and providing the customers' requirements of petroleum products. Moreover, it supports more than 9.2 million jobs globally and accounts for 7.5% of the Gross Domestic Product GDP (Al Rousan, Sbia et Tas, 2018). The petroleum sector comprises complex supply chains starting from exploration, production, transportation, inventory, refining, petrochemical, and marketing. Recently, the petroleum industry has grown increasingly complex due to the high competition in a globalized market, environmental regulations, and fluctuating demand and prices (Hussain, Assavapokee et Khumawala, 2006; Baumeister et Kilian, 2016). Also, during the spread of COVID-19, crude oil prices oil has been affected by a sharp drop in the financial markets. Furthermore, that has led to a sharp decrease in oil services with an employment decrease in jobs and higher probabilities of risks (Ponkratov et al.,2020). Therefore, it is essential to identify an alternative investment instrument in oil markets to mitigate the risks revisit the resilience COVID-19 event (Dutta et al.,2020).

The world energy demand continues to rise steadily year by year. Therefore, petroleum products are expected to increase by 12 million barrels/day (12 MMbbl/d) for the long-term demand forecast to reach 110.6 MMbbl/d by 2040 (Dale et Fattouh, 2018). This growth in the petroleum sector can attract many investments, which requires a unique strategical plan to comprise the demand and supply (Hvozdyk et Mercer-Blackman, 2010). According to the International Energy Administration (IEA) estimates that the investment in the energy section should be around 9.6 trillion from the total of $22 trillion in the period (2006 – 2030) (Conti et al., 2016).

Supply chain management in the petroleum industry is a complex process with a high interconnection between three sectors: upstream, midstream, and downstream, as showing in

Figure 0.1. The upstream sector is responsible for exploration, drilling, crude oil extraction, and production activities up to the petroleum terminal. The midstream sector covers transportation by pipeline, rail, oil tanker, or truck, and storage. The downstream sector includes refinery transformation activities, petrochemicals, distribution, wholesale, and marketing (Attia, Ghaithan et Duffuaa, 2019b; Fernandes, Relvas et Barbosa-Póvoa, 2014).

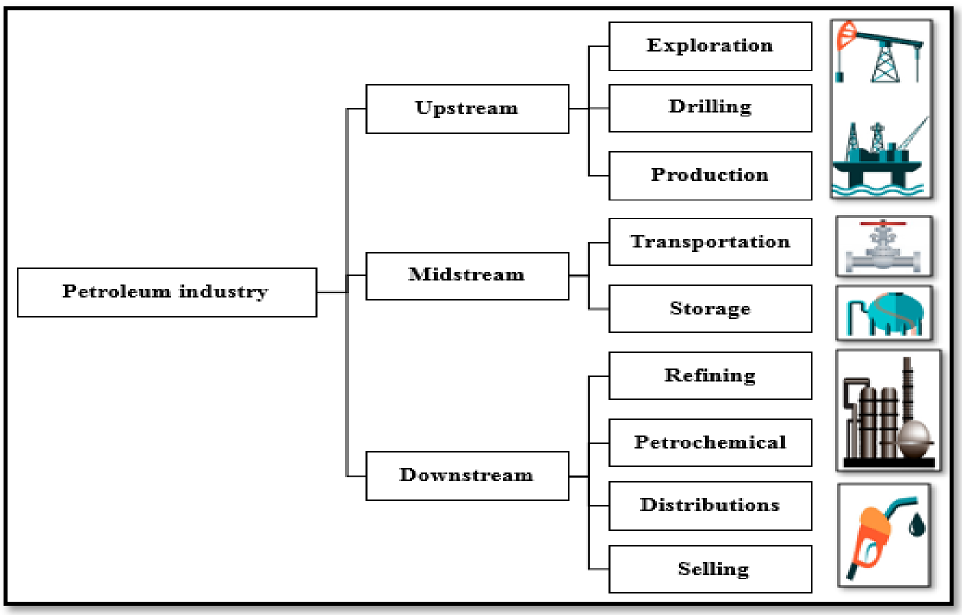



Figure 0.1 Supply chain network in the petroleum industry

Nowadays, the supply chains worldwide face pressures to green their operations and implement the highest environmental protection standards, which requires efforts and long-term planning (Mani, Agrawal et Sharma, 2015; Y. Lakhal, H'Mida et Islam, 2007). Further, the new regulation pushes the sector to limit the $CO_2$ emission, but the problem is challenging to know the value of the $CO_2$ emission reduction target. Therefore, the main problem is the uncertainty regarding introducing new regulations and the $CO_2$ reduction target to fix for the future?

Hence seeking sustainability nowadays in the petroleum industry is essential because it represents the integration of supply chain activities to fulfil the three dimensions of sustainable development; economic, environmental, and social (Florescu et al., 2019). In this regard, there are many different solution approaches (methods) for the sustainable petroleum industry:

- Carbon footprint and Low-carbon economy (Seixas et Ferreira, 2020),
- Climate change response: green energy and low-carbon policies (Newbery, Qi et Fitt, 2016),
- Sustainable strategies and eco-technologies (Betanzo-Torres et al., 2021).

Moreover, sustainable supply chain management (SSCM) could be one solution because it deals with supply chain flow, capacity, and logistics. From this matter, many studies have been applied SSCM in the past to solve the issues regarding many sectors such as Food Beverage (Tuljak-Suban, 2016); Healthcare (Duque-Uribe et al., 2019); Industrial Manufacturing, Industrial Equipment (Flores et al., 2020); Transportation ( Ren et al., 2019).

This study's key motivation comes from the solid global desire to reduce the impact of air pollution, whether in the present or the future. The environmental issues related to the petroleum industry are mainly greenhouse gas (GHG) emissions, groundwater contamination, waste streams, solid waste, and marine spills (Sahebi, Nickel et Ashayeri, 2014a). Hence, $CO_2$ emissions count for a significant percentage of GHGs and are responsible for increasing global warming (EPA, 2019). For instance, the refining sector has the largest source of emissions, and it was representing about 6% of the global $CO_2$ emissions, close to 1 billion tons of $CO_2$ per year (Chan et al., 2016). Therefore, the petroleum industry should balance the sustainability dimensions in a highly dynamic market scenario. So, the effective implementation of sustainable practices in the petroleum supply chains is a real need.

**Research problem description**

They consider the importance of the petroleum industry and the great need for achieving sustainable development in supply chain activities. Further, this area of research requires further attention. It will help the decision-makers to be able to make robust decisions based on quantitative methods to be more resilient and sustainable (Lebel et al., 2006). The supply chain management in the petroleum industry consists of the same decisions (strategic, tactical, and operational) found in most industries. In this perspective, planning decisions need to be restructured throughout the supply chains at the sector level. This includes strategic choices to determine the location, capacities, and extracting quantity. Simultaneously, decisions regarding tactical planning involve the flow of oil from wells to the refinery and product shipment to the demand centres and modes of transportation. Also, the operational decisions at this level are regarding short-term activities such as determine the quantity of the flow between nodes, amount of the inventory, transportation, and routing plans at each level of the supply chains (Ribas et al., 2012).

Due to the fluctuations in crude oil prices, the supply chain must react rapidly to guarantee profitability. More specifically, oil price reduction lead to limit exploration activities. However, the crude oil price increase pushes for much focus on improving the research for alternative energy. Further, the world's population is expected to reach nine (9.0 billion) by 2050. That means more people need more demand to generate the power energy for mechanized lifestyles, which has a significant contributor to global warming. As a result, it is expected that the energy demand will increase by 1.2% per year by using 35% more energy levels (Conti et al., 2016). From an environmental perspective, the crude oil industry faces difficult decisions due to the high consumption of energy and, at the same time, high levels of GHG emissions. Figure 0.3 gives a general overview of GHG emissions from crude oil activities.

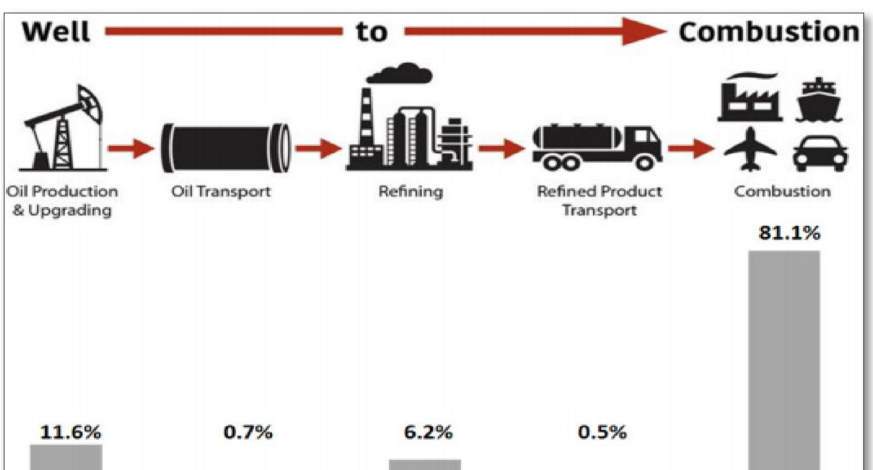



Figure 0.3 Estimated GHG emissions from crude oil activities
taken from Forrest et Rocque (2017)

Current and future environmental regulations aim to provide a safe and secure working environment that affects the decisions faced by this industry. After the ecological disaster, especially in the Gulf of Mexico and the Northeast Brazil oil spill, multiple countries have taken environmental legislation into account. Carbon efficient environmental regulation aims to provide a safe and secure working environment that affects in decision face. Indeed, after the cofide19 disaster, especially in some governments. For example, the US government pushes petroleum companies to meet higher standards in their operations. Also, Canadian oil sands companies face the cancellation of the Keystone XL pipeline from Alberta to Gulf Coast refineries. Thus, petroleum producer countries need to revise their strategy for (exploration, production, refining, petrochemical, and transportation).

A complex system is a part of the system which including different elements with complete connection to each other and working together (Ladyman et al., 2013). The structure complex system has many variations with multiple interactions between many different components. However, in our case, the strategy is so complex to develop. It requires a comprehensive methodology to establish the link between the planning process demand, distribution, and network capacity with environmental performance. Indeed, research work still has some gaps. The literature is not well developed, and understanding how to manage the petroleum sectors, especially from the environmental perspective (Sahebi, Nickel et Ashayeri, 2014).

Recently, several academic studies have proposed optimization models. Many of these models focus on applying mathematical programming within sustainable supply chain planning in the petroleum industry. The mathematical programming model aims to help decision-makers select alternative plans in various conditions, such as economic strategy related to maximizing the profit under the sources of emissions or changes in environmental regulation. However, the models that can integrate all sectors in the petroleum industry (crude, refinery, and petrochemical) are limited. The only study that tackles the three sectors was developed by Al-Othman et al. (2008); however, the study only considered the economic perspective and neglecting environmental and social. Therefore, the need for an integration model to discuss and evaluate economic and environmental decisions is necessary. This integration model could have more complexity with a better response. The model could be a solution to answer the challenge facing the supply chain network. For this matter, the Libyan petroleum industry is taken as a case study in this research. The Libyan petroleum sector is the most crucial, which counts for 80% of (GDP) and represents 95% of export incomes (Baffes et al., 2015). Indeed, petroleum products are used to transport and create medicines in our daily lives. Further, Libya is a member of the OPEC organization and classified as one of the top 20 producing countries. In 2018, production reached 1,039 MMbbl/d. Libya has Five big basins with a capacity of 60 billion bbl integrated into 100 wells to extract very good quality crude with API ranges between 34° to 44°, as showing in figure 0.4 (Barltrop, 2019).

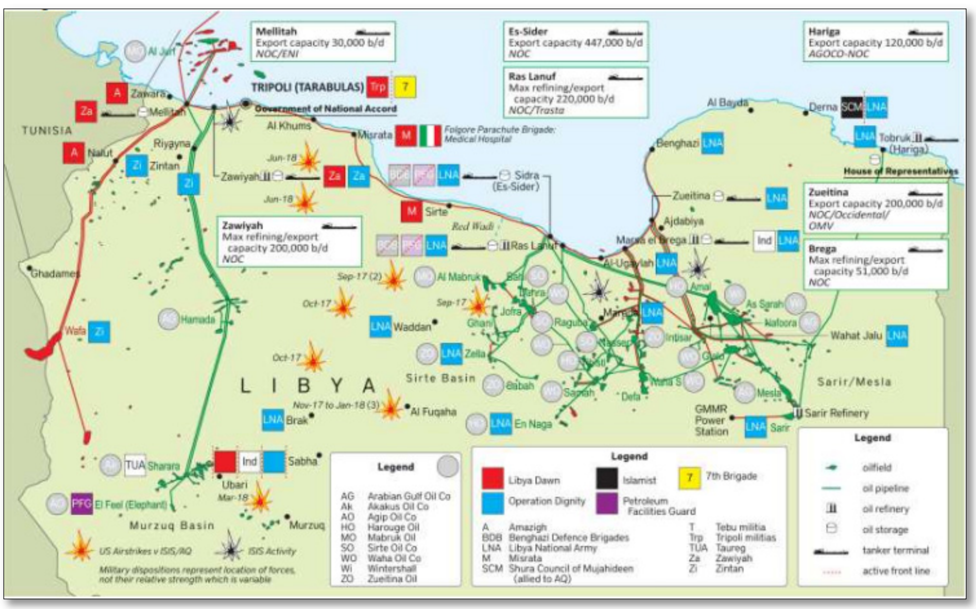



Figure 0.4 Libyan petroleum network
Taken from (Barltrop, 2019)

Indeed, this huge production leads to significant carbon emissions emitted from this sector. However, the sector faces complex challenges due to environmental issues with a considerable rise in GHG emissions, mainly $CO_2$ (CBL, 2007; Elhage et al., 2008). According to the U.S. Energy Information Administration, Libya is classified as 56th from 225th of the most polluted countries with 60.60 million tons annually (MT/y) of $CO_2$, which contributes to 0.22% of global emissions (Table 0.1) (Nassar, Aissa et al. sadi, 2017). For this matter, the Libyan government needs to implement emissions reduction policies and strategies to reduce GHG emissions by achieving the best strategy to decarbonize the supply chain under the uncertainty of environmental regulations.

Table 0.1 The most polluted countries (Nassar et al., 2017)

| Rank | Country | Production (Mbbl/d) | $CO_2$ (MT/y) | % of global emissions |
|---|---|---|---|---|
| 1 | China | 4,980,650 | 9057 | 27.2% |
| 2 | United States | 15,043,000 | 4833 | 14.6% |
| 3 | India | 1,643,000 | 2077 | 6.8% |
| 4 | Russian | 10,800,000 | 1439 | 4.7% |
| 5 | Japan | 4.040.000 | 1148 | 3.3% |
| 6 | Germany | 46,839 | 732 | 2.2% |
| 7 | Iran | 3,990,956 | 563 | 1.9% |
| 8 | Canada | 5,662,694 | 541 | 1.85% |
| 9 | Saudi Arabia | 12,000,000 | 527 | 1.8% |
| **56** | **Libya** | **1,100,000** | **60.60** | **0.22%** |

Furthermore, environmental management has been widely ignored in the Libyan petroleum sector, with very slow in implementing modern concepts to meet the standards and requirements. Even though Libya is a member of the Kyoto Protocol, aiming to manage global warming, and also signed the Paris agreement on climate change toward further international progress in global warming. Still no effort to engage or reducing GHG and promoting sustainable development by the Libyan petroleum sector (Emodi & Boo, 2015; Thomas & Dargusch, 2011; Zahari & Shurbagi, 2012).

Currently, Libya has five refineries, mainly concentrated in the Northeast of the country, with a total refining capacity of 380,000 (bbl/d). The Ras Lanuf refinery is the largest refinery, with a crude oil throughput of 220,000 bbl/d. Also, three petrochemical plants with a total capacity of 78, 033 bbl/day. These plants' operations can contribute to the increase in GHG, mainly $CO_2$. According to Nassar, Aissa et al. sadi (2017), figure 0.5 presents the contribution of the amount of $CO_2$ emissions emitted to the environment regarding many industrial sectors. The highest emission emitted comes from the electricity sector, which is the primary energy source of the petroleum industry. The power plants generate Libyan electricity by fuel oil or natural gas with a total capacity of 6.8 GW. Further, the refinery industry emits 1.19 (MT/y), representing 2.3% of the total $CO_2$ emissions.  Even though the refinery sector has the lowest capacity among all sectors, it is important to implement technology to reduce GHG emissions by every single refinery unit to meet the standards (US EPA publication AP-42; EPA, 2015; Cai et al., 2014).

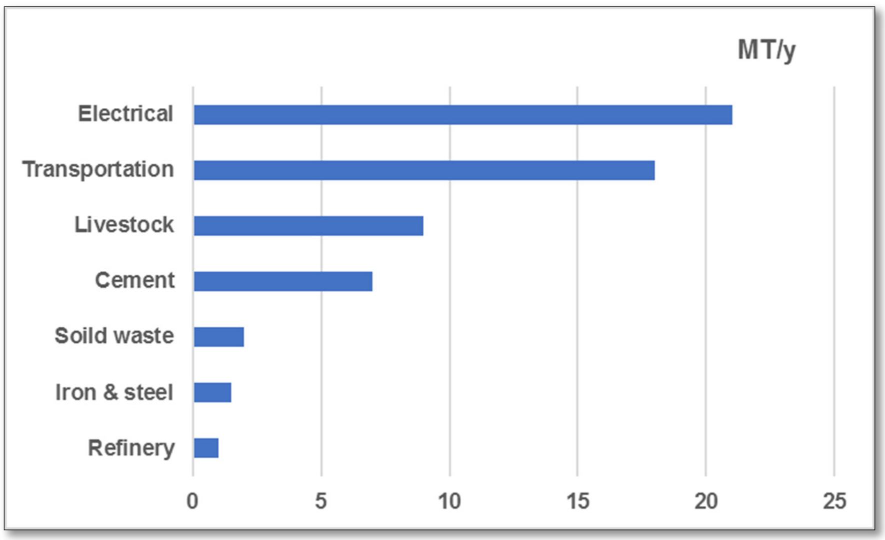



Figure 0. 5 The annual $CO_2$ (MT/y) emitted by Libyan sectors
Taken from Nassar, Aissa et Alsadi (2017)

Furthermore, the Libyan petroleum industry has another environmental impact related to upstream and downstream activities. Large volumes of wastewater are generated from crude oil extraction, refineries, and petrochemical operations. However, it remains a challenge for the industry to minimize its impact on the environment because it disturbs land and marine ecosystems. Further extracting actives produced more water than oil with an average of (1 MMbbl) of crude oil and (4 MMbbl) of produced wastewater, which causes a significant problem (Saad *et al.*, 2018). Therefore, it is important to select a suitable methodology to satisfy the objectives, aims, and research questions in this study.

Thus, a system thinking approach and a sustainable supply chain management perspective have been taken to tackle these problems. Since the petroleum industry is still developing and needs to manage its supply chains, supply chain management is essential to gain more importance in the global market. We also assume that actions (planning decisions) could be made through the whole sector (country level) to overcome these issues. Therefore, the main goal of the proposed research from the economic perspective is to help the decision-makers to identify suitable extraction, production, and distribution plans to meet environmental regulations. More specifically, the objective is to identify the decisions related to the flow between nodes, production capacities at each level, and how to satisfy the demand to minimize all sectors' total cost.

However, as mentioned above, pressure comes from different rules to push the petroleum sector and its activities into greener operations. The new environmental regulations ask to reduce the GHG during the supply chain activities (Knittel, 2012). Therefore, increasing interest in sustainable practices in the petroleum industry will allow us to identify the opportunities for improvement to sustainable supply chain management. Indeed, sustainability plays a vital role in the direction of a successful and responsible business, even in the petroleum industry. Sustainable development must address a global approach to tackle challenges with purely economic and minimal impact on the environmental problems (Lim, Jørgensen, & Wyborn, 2018).

**Research Objectives**

The research aims to propose a decision tool to assess different transformation plans for the petroleum sector under the uncertainty of environmental regulations. To achieve this primary objective, we define the following sub-objectives:

- Propose a framework for sustainable supply chain planning in the petroleum sector,
- Develop a data-driven and generic decision-making model for eco-efficient supply chain planning,
- Demonstrate the model’s applicability to evaluate two options, Carbon capture and storage (CCS) and Green (Solar) energy, to decarbonize the Libyan petroleum supply chain.

To achieve these objectives, three (3) main research questions (R.Q) have been raised regarding this study:

- **R.Q 1:** What are the main components of developing sustainable supply chain planning models in the petroleum sector?

- **R.Q 2:** How to develop a data-driven decision-making tool for eco-efficient supply chain planning in the petroleum sector?

- **R.Q 3:** How to apply the proposed tool with real data to establish the "best strategy" to decarbonize the supply chain in the petroleum sector under the uncertainty of environmental regulations in the case of Libya?

**Research methodology**

A system thinking-based-methodology approach is adopted to solve this problem because it looks at the overall network rather than specific system parts (Grösser, 2017). Moreover, it tackles complex issues and risk factors to highlight the change in the organization's performance. Also, it helps practitioners to bring together many different parameters to identify problems and solutions to challenges (Rebs, Brandenburg, & Seuring, 2019). Since there are other environmental risk sources, the new regulation pushes the petroleum sector to limit $CO_2$ emissions. But the problem is challenging, and we need to know the value of the $CO_2$ emission reduction target. So, to solve these issues, Libya went and signed the Parise agreement and tried to implement sustainability practices since it was ignored in the past. Based on that, our methodology follows the system thinking approach to develop a supply chain in the planning model to integrate (economic and environmental) decisions to establish or propose strategy planning.

Therefore, the main objective of this research is to propose and evaluate a transformation plan for the petroleum sector under the uncertainty of environmental regulations. Consequently, we propose a four-step methodology that follows the system thinking approach (Rebs, Brandenburg, & Seuring, 2019) illustrated in figure 0.6. The first step investigates the literature review from a modelling perspective to identify the research gaps, opportunities, modelling issues, system definition, and delimitations. In the second step, we develop a mathematical model to evaluate the performance from an economic perspective to get a baseline model. We will extend the economic model by adding an environmental dimension to get an eco-efficient model in the third step. In the last step, once the model is developed, we will validate it and use a real data to establish the best strategy for the supply chain to achieve the reduction target.

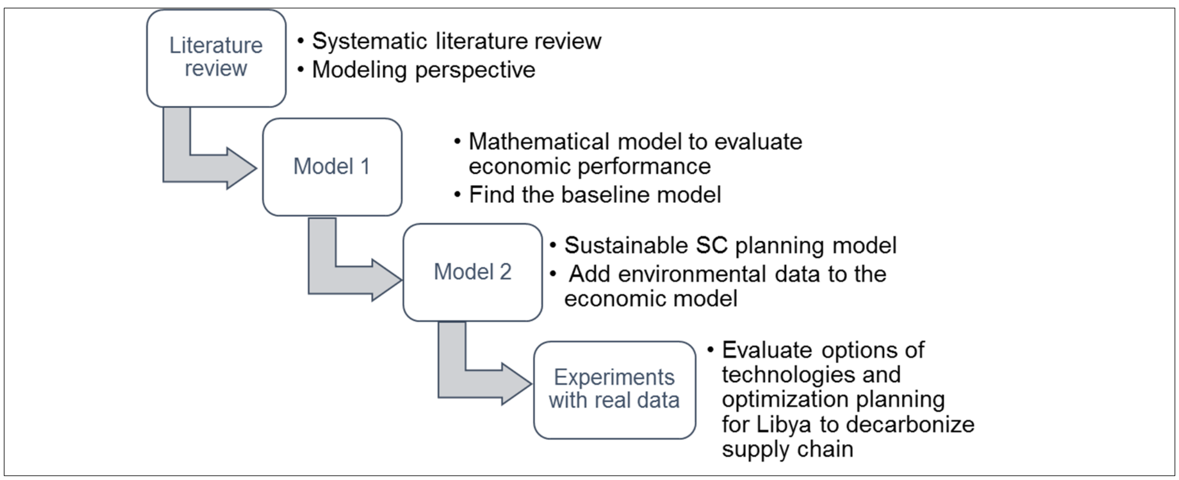



Figure 0. 6 General methodology

In the first step, we follow a specific methodology by doing a systematic literature review (SRL) using qualitative and quantitative methods. The main scope is for mathematical models for the strategic and tactical supply chain in the petroleum sector to capture the relevant system components by following these sub-steps: the papers were selected based on applied mathematics, management, and engineering journals in the field petroleum industry. Also, based on chosen keywords, with a time frame of 10 years covered from 2010 to 2019 period to get a total of 158 references by using the English language. After that, we excluded the papers that do not fulfil our research to come up with 23 references.

The research methodology consists of a structured review covering sustainable supply chain planning models in petroleum industry research. It starts by identifying keywords based on which papers are selected using the citation method (Pittaway et al., 2004). SLR is a valuable tool that can help the researcher comprehend diversity regarding knowledge and historic development regarding a specific research topic. Moreover, a literature review helps the researcher identify further research opportunities by analyzing research gaps in the existing knowledge. The systematic content analysis process selected to develop the required methodology of this work consists of the following steps (Junior et Godinho Filho, 2010; Krippendorff, 1980): material collection, descriptive analysis, category selection, material evaluation.

As a result of this step, we have to investigate the selected papers to get the main finding systematically. A taxonomy framework that includes the main component guides us to structure our new model (Purpose of the study, performance, Supply chain structure, decision phase, modelling approaches, horizon, applications, and environmental evaluation). Further, the selected peppers were analyzed to identify the research gaps, opportunities, modelling issues, and future research.

In the second step, and based on the framework developed in step 1, we define the physical supply chain by collecting data based on the Libyan petroleum sector case study with the collaboration of (NOC). Some assumptions will be taken as input to develop the supply chain structure at different levels (crude, refinery, and petrochemical). Next, we added some parameters and identified the decisions, constraints, criteria, objective functions, and equations. In this step, we will consider only the economics perspective to get a new generic Mixed-Integer Linear Programming (MILP) deterministic model (Baseline model). The main goal of this model is to help the decision-makers identify the decisions related to the production flow between nodes, production capacities at each level, and how to satisfy the demand to maximize the profit from local and international markets under some risky situations. Solving and running the model with different scenarios help to see the system's dynamic and validate the model from an economic perspective.

In the third step, we extend the economic model to include environmental demission to get the (eco-efficiency model) by adding the necessary environmental data. After that, we define a new investment decision in technology selection at each level (crude, refinery, and petrochemical). Finally, we will use multi-objective Linear programming to balance cost and emissions. Since we get this model, we will use it to establish the best strategy for decarbonizing the supply chain in the Libyan petroleum sector. Various kinds of risks can occur at any time and certainly not possible to be avoided. This study considers the uncertainty related to the choice of pollution control mechanism that can be influenced by economic risks, including oil price collapse, loss of demand, high operating costs, disasters, and shortages in some geographical locations. These can significantly affect exploration, development, and production.

The optimization model aims to help the decision-makers identify investment decisions at each sector, the production flow decisions between nodes, production capacities at each level, and how to satisfy the demand to local and international markets. In the third step, we integrate the environmental dimension after gathering the baseline model's data. The goal is to study the effects of environmental regulation and estimate the cost change after implementing mitigation strategies for each petroleum sector. The Libyan petroleum sector used a case study to invest and evaluate different technologies to move toward more sustainable and greener. Finally, in step 4, we provide some sensitivity analysis to study the impact of uncertain parameters such as demand and emission factors on planning decisions and model solutions. According to the literature review and analyzed the papers, we figure out that there are many options for technology reduction that needs to consider and integrate into our eco-efficient model. The most interesting ones for the sake of this study are CCS and solar energy. Therefore, we evaluate these options of technologies for optimization planning in Libya to decarbonize the supply chain. Once we developed the model and validated it, we create an experimental plan with real data to establish the best strategy for the supply chain to achieve the reduction target. Moreover, we provide sensitivity analysis to study the effect of uncertain parameters such as demand and carbon emission factors.

## Structure of the thesis

This thesis consists of six chapters structured as follows after the introduction that states the problem description, objectives, research questions, and discusses the research methodology adopted in this study. Chapter1 presents this study's background and introduces the petroleum industry to the reader to follow the concepts, even if he is not a specialist in this area. Chapter 2 provides a systemic literature review on the sustainable supply chain in the petroleum industry from a modelling perspective to highlight the knowledge and fill our research gaps. Chapter 3 develops an optimization mathematical deterministic model (model 1) to evaluate the performance from an economic perspective. Initial experimentation considering the Libyan case study is used to validate the model and obtain a baseline model. Chapter 4 extends model 1 to include the environmental dimension and develops the eco-efficient model (model 2). Chapter 5 presents a detailed experimentation process to analyze two carbon abatement options (CCS and solar). It also evaluates the impact of uncertainty on these results. Finally, the main contributions to knowledge and the limitations of the research were also discussed. Finally, the conclusion summarizes the main results with a discussion about future research directions.

## Summary

This chapter represents a brief overview of the nature of the study. It starts with providing a detailed introduction to the research associated with the petroleum industry. Then, the chapter provides the research problem description in general and in the Libyan petroleum industry in particular. Subsequently, the chapter moves to identify the research objective and the research questions to be investigated in this study. Finally, a methodology followed by solution steps to cope research objective and the research questions to handle the current challenges.

# CHAPTER 1

# BACKGROUND

## 1.1 Crude oil industry

Petroleum is called crude oil, and it has the name black gold, which is a thick, flammable liquid, dark brown, and is found in the uppermost layer of the earth. It consists of a complex mixture of hydrocarbons, especially of the alkane's series, but differs in appearance, composition, and purity significantly from place to place. Petroleum is the raw material for many chemical products, including fertilizers, pesticides, and plastics. Crude oil is extracted in special ways from the earth's upper layers to produce different types according to geographic location and extraction techniques. Global energy statistics showed that oil is one of the most important and valuable primary energy sources (Dudley, 2018).

Also, it plays a significant role in economic, political, and social by providing about (35%) of the universal energy (Ahuja et Tatsutani, 2009). In the last 100 years, the oil industry has developed rapidly, and most nations are racing for exploration and extraction. The world demand continues to rise steadily year by year. According to the Petroleum Exporting Countries (OPEC) Organization, the oil demand has increased from (36% to 55%) in (2016). This growth means that worldwide demand for petroleum products will remain high (Saboori et al., 2016). It requires investing heavily to develop strategic decisions to meet the demand and solve the petroleum industry's issues. Also, it attracts many investments and development into a country; however, if these countries are not established well, it causes destruction and conflict. The investment decisions are directly related to the demand for products, oil production, market prices, and regulations.

The IEA (International Energy Agency) stated that to meet the global energy, the expected investment needs in the upstream sector will be (700 M $) each year until 2040 (Mojarad, Atashbari et Tantau, 2018).

The total cost related to petroleum activities in each level is (Fixed cost, the variable extracting cost associated with wells, and the variable transformation cost associated with refinery and petrochemicals (API, 2015). However, the oil industry faces a challenging task to remain competitive in the global market due to fluctuating demand and prices, and nations and investors have significantly lost this investment. This encourages researchers worldwide to devolve a sustainable plan that overcomes such an issue in the future.

## 1.2 Characteristic of the petroleum industry

The petroleum industry has unique characteristics that make a significant difference from other industries in terms of volume and values (Varma, Wadhwa et Deshmukh, 2008). Further, these characteristics can play an essential role in their supply chain regarding high transportation costs, increases the risk of handling and manufacturing, lack of management, operation, and sharing information. Therefore, it enjoys a relatively low unit cost due to the standardization of the process. Sources of profitability: Due to the lack of product variety, significant profitability sources come from cost reduction production, transportation, and efficiency.

## 1.3 Crude oil classifications

The classifications of the crude oil types are based on their geographical source and based on density and specific gravity. American Petroleum Institute established API standards to classify the different types of crude oil. The API number is used to measure the crude oil density in comparison to water. Light crude oil is depending on its API that having higher than (31.1°). It has low viscosity and low wax content as well. So, this kind receives a higher price on the market because it has an effortless ability to be refined with a higher percentage of products with a less negative impact on the environment. Medium crude oil has an API between (22.3°) and (31.1°); meanwhile, heavy crude oil has an API below (22.3°), which does not flow easily and requires more advanced techniques and extra processing costs.

Moreover, it requires a large amount of energy and water. So, it has a more negative impact on the environment regarding solids waste, water, and GHG (Gounder, 2019). Therefore, this industry's primary challenge is choosing the best technologies for production, upgrading, and transporting heavy crude oil to minimize the environmental impact (Neff et Hagemann, 2007).

### 1.4 Crude oil industry sectors

The oil supply chain includes extracting, production, domestic and international transportation, inventory, and distribution. The goal of supply chain management in the oil industry is to achieve optimum exploration, production, and efficient processing at the lowest cost possible. Further, it consists of three segments; upstream, midstream, and downstream. They start from exploration and production, move to the refinery and petrochemical industry, and terminate at the markets and demand sources (Beiranvand et al., 2018).

#### 1.4.1 Upstream

The upstream sector is the part of the petroleum industry responsible for finding crude oil underground or underwater. This sector includes all activities related to the exploration and production of wells (location, operation, and management) and is followed by the production, which is the actual extraction of crude oil from the ground. The exploration stage involves seismic and geological operations. The production stage concerns the exploitation of crude oil from the reservoir by drilling (Sarris *et al.*, 2018).

- **Exploration**

Exploration is the process of searching the crude oil under the Earth's surface and making sure that the well has enough quantity. The methods of exploration are still involved and require extensive spending. Technological development has reached a long way in conducting satellites, gravity, seismic, remote sensing devices, and 3-D and 4-D seismic technologies. However, these technology methods aim to increase the efficiency of exploration and drilling activities and reduce effects on the environment by making it possible to discover oil reserves while drilling fewer exploratory wells (Sarris *et al.*, 2018).

- **Production**

Production activities for crude oil are complex processes in terms of wells drilling. Therefore, crude oil is produced by using several types of drilling methods regarding geographic location. The most common drilling methods are horizontal drilling or hydraulic fracking drilling to extract crude oil mixed with water, sand, salt, and natural gas. So, each well should consider the operational costs, hardware damage, reservoir performance, and environmental requirements.

### 1.4.2 Midstream

Midstream is the second one, and in some cases, integrated with the upstream sector. The mean goal is to gather crude oil produced in the upstream sector and moved either to exportation points or to the refinery. It consists of activities such as storage tankers, transportation, and distribution. Transport carries crude oil to different refineries, terminals for storage, and international markets (Sahebi, Nickel et Ashayeri, 2014). The midstream provides an essential link between petroleum-producing areas and consumers. In some cases, the distance could be so long, which is the main reason for having a longer lead time than in other industries. Also, they provide technologies and equipment to increase efficiency and communications to avoid pipeline leaks and other issues (Adegboye, Fung et Karnik, 2019).

### 1.4.3 Transportation

Transportation networks in the petroleum industry mainly include pipelines, rail, shipping, and tracking, as shown in figure 1.1 (Association, 2013).

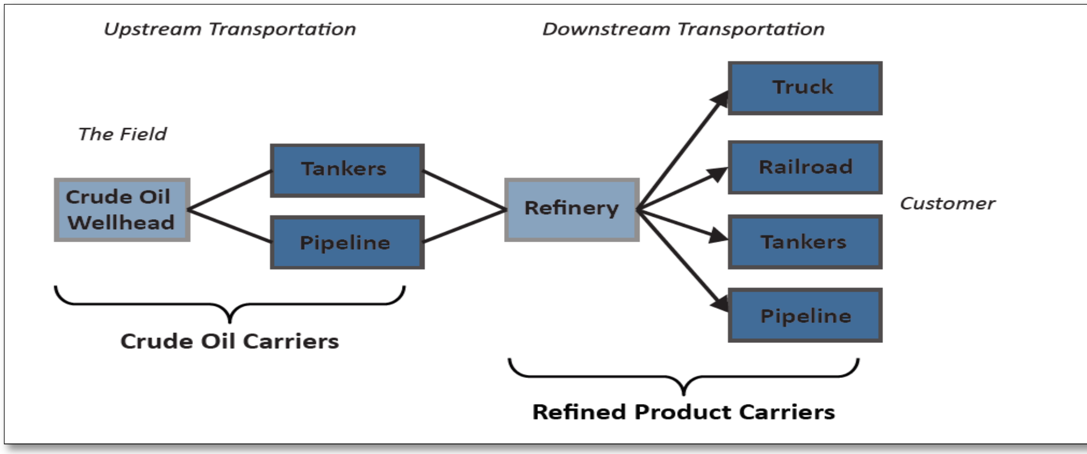



Figure 1.1 Upstream & downstream transportation crude oil and refined products
Taken from (Association, 2013)

**Railways**

Railway transportation is one of the fastest and independent methods that are not affected by weather conditions. This method is not reliable for transporting large quantities of petroleum, such as raw material and petroleum products like gasoline, liquid petroleum gas, and jet fuel. However, carbon emissions and dangerous accidents to the public are some significant disadvantages to rail transportation. In such a way, even in highly developed railway systems, petroleum suppliers prefer to use pipelines.

**Pipelines**

Pipelines networks are a critical part of petroleum infrastructure and the most widely used for petroleum transportation. It can be ground and underground and lay according to network design. It is the most efficient economical way to move large volumes of petroleum from upstream areas to refineries and petrochemical plants because it is the safest and environmentally friendly way, figure 1.2 (Cross et al., 2013). Several technologies have been introduced to improve pipelines' quality to allow the flow to go smoothly from the production point to the distribution depot. Also, to meet the environmental conditions to ensure safe avoid pipeline failure causes leaks in pipeline networks (Adegboye, Fung et Karnik, 2019).

**Trucks**

This method is the most limited oil transportation method and uses mainly local in terms of storage capacity. Further, trucks have the most excellent flexibility for transporting refinery products from storage tanks to end customers. However, several regulations and training are needed to minimize the environmental, public impact, and damage to the roads.

**Maritime**

The importance of this (R.S) way where oil transport over land is not possible, transporting oil oceangoing and large quantities ships are used. It designs explicitly to carry massive crude and its products from the producing country to consumers. Also, the ship's tanker can take raw materials and natural gas feedstocks to petrochemical plants. The giant tankers often ship quantity between (2 to 3.7 MMbbl) of crude oil at once (EIA, 2016). Compared to a pipeline, barges are cheaper by 20-35%. However, several incidents have been reported, requiring tight regulation to avoid such significant incidents and environmental concerns (Bp gulf Mexico).

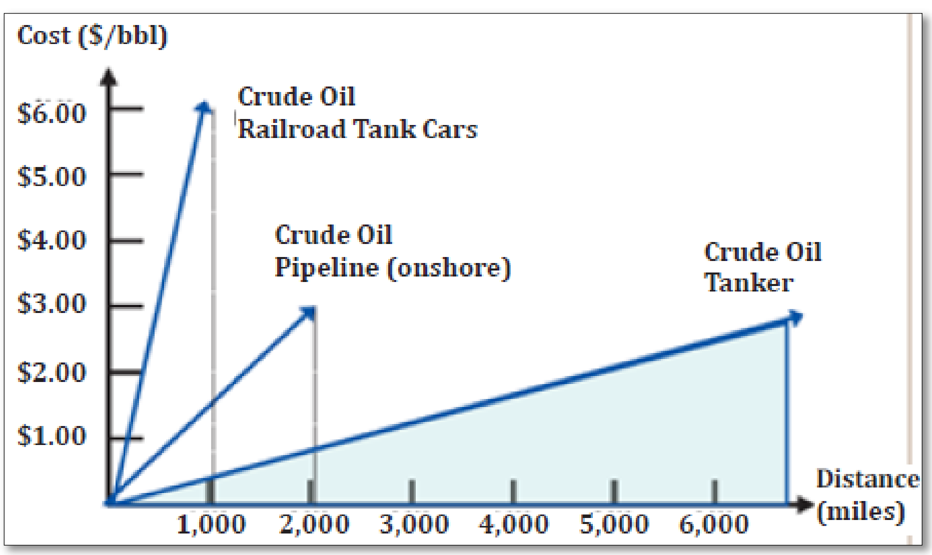



Figure 1.2 Crude oil transportation costs
taken from (Association, 2013)

### 1.4.4 Storage

The main goal of storage facilities is to balance the supply and demand of crude oil until it is ready for the following processor re-scheduling of transportation. The selection of a storage tank is a complex problem. Tanks could be in different types and sizes. They are classified based on many criteria, such as service and environmental conditions. Further, tanks are available in each sector, such as crude oil products, refining, and petrochemical and chemical manufacturing.

## 1.5 Downstream

The downstream sector is the largest in the petroleum industry. The downstream sector is the third level of the petroleum industry, including refining, petrochemicals, and final product distribution. The downstream stages contain complex prosses that require high technology prosses that can significantly impact the economy and environment.

### 1.5.1 Refining

The main goal of the refineries is to convert the crude oil into several valuable products such as ( gasoline, naphtha, liquefied petroleum gas (LPG), and jet fuel) at a low cost with minimum greenhouse gas emissions (Hadidi *et al.*, 2016). However, their processes are so complicated with multiple operations systems. It has four basic functions: distillation, conversion, cracking, and treatment. It requires energy and many support facilities such as secure land, electricity, steam, water, hydrogen, etc.

The basic refinery structure is designed to contain four primary units' distillation, conversion cracking, and blending.

- **Distillation:** It is the primary process to separate crude oil under different heat and pressure in a sizeable fractionating tower. The product separated and leave the tower based on its evaporation temperate point and density. The residual goes to the tower from the bottom to another unit for a further separation step.
- **Conversion:** Different parts of crude oil have different boiling points. As the temperature rises, these different fractions are separated and quickly rise to the top of

the distillation towers. Refineries also use chemical agents to help for removing carbon or adding hydrogen conversion.

- **Cracking:** It is vital uint in refineries. The high temperatures and chemical catalysts reactions are used for crushing the heavy crude oil with high IPA into lighter petroleum products, gasoline and diesel fuel.

- **Blending:** The final phase is treatment. In this step, the fractions produced during separation are treated to improve their quality by blending with other elements to produce the final products.

Every refinery has different units or sizes to determine the quality of crude and product produces. The most basic one is topping the refinery. It is the most straightforward kind and mainly revolves around the distillation column. The products produced are naphtha and other intermediate products, but not gasoline. A flow refinery layout illustrated in Figure 1.3.

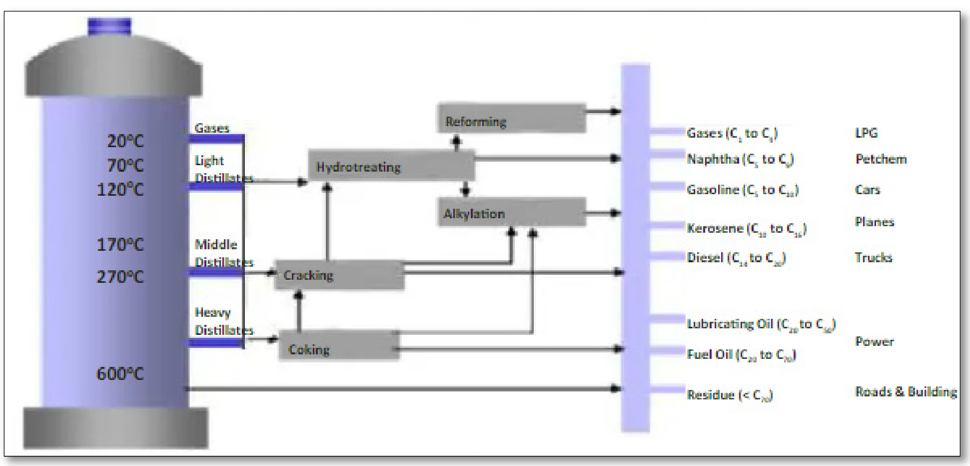



Figure 1.3 Refinery layout
Taken from (Association, 2013)

Further, hydro skimming refineries are more advanced, including conversion, hydrotreating, and reforming units. The main goal is to produce gasoline products with low carbon specifications. On the other hand, upgrading/conversion refinery, which is considered an expensive one, includes cracking or coking operations to convert or crack long-chain that can be used to produce petrochemical feedstock. The efficiency of this refinery depends on demand and supply because it needs more energy and workforce. Finally, the cooker refinery is the most advanced oil refinery, and it upgrades most of the fuel oil to lighter products. It is designed to have the ability to handle different available types of crude, from light to heavy. Also, it requires lower investment costs, designed for lower-local demand, shorter schedules, and higher quality products. The refineries sector challenges are increased oil prices and demand, new demand for petrochemical products, new environmental regulations, unsustainable supply chain, environmental disaster, and political unrest.

### 1.5.2 Petrochemical

Petrochemical is one of the most important industries for economic development in each country because it has several linkages with other sectors. The structure of the petrochemical industry is so complex because the production process is considered one of the most energy-intensive operations. Figure 1.4 shows the layout of the petrochemical plant.

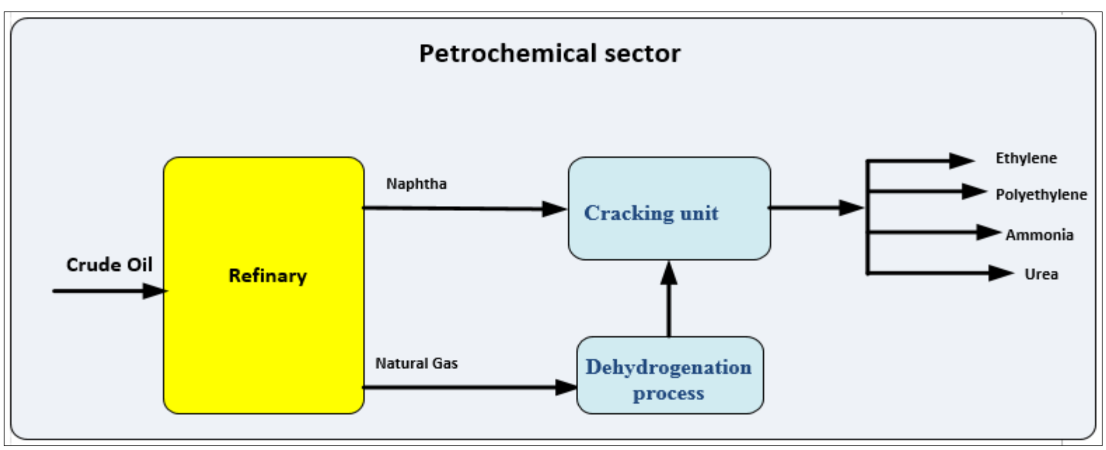



Figure 1.4 Petrochemical plant layout

The primary raw materials are natural gas and naphtha to produce valuable products such as ethylene, propylene, styrene, and butadiene. Petrochemicals plants are usually integrated within or nearby a petroleum refinery. This integration allows both plants to exchange streams by using transformation technology with different processes, such as a combination of reaction, distillation, absorption, filtration, and screening operation (Nasr *et al.*, 2011).

### 1.5.3 Distribution

The distribution network is connecting routes between wells, storage tanks, and international customers. Also, between refineries, tanks, and customer areas. The nodes represent (terminals, plants, distribution centers, and global markets) connected by transportation links. The process started by unloading petroleum products from the suitable transportation mode and sending them directly to the market through the right tank. Several factors are affecting the distribution task:

- The number of products to be transported,
- Maximum storage capacity for each product,
- Pipeline capacity,
- Time horizon to be considered,
- Initial inventory of each product,
- Daily demand.

## 1.6 Factors affecting the supply chain in the petroleum industry

### 1.6.1 Sustainable supply chain management (SSCM)

Academics and practitioners consider the opportunities offered by decision-making tools for planning sustainable supply chain management in modern industries and organizations. Indeed, It is essential to integrate environmental and social issues besides the traditional economic indicators to define sustainability dimensions into strategic and tactical decision-making to get a long-term model (Reefke, Ahmed, & Sundaram, 2014). There are many definitions of SSCM in literature. For example, (Metta & Badurdeen, 2011) defined it as "*the management of material, information, and capital flows and cooperation among companies along the supply chain while integrating goals from all three dimensions economic, environmental, and social.*" Today, the petroleum industry has one of the most complex and advanced supply chains around the world. The petroleum industry's role in sustainable development should meet the global society's needs for crude oil and its products at a reasonable cost, safely, and with minimal impact on the environment.

Therefore, SSCM combines all the efforts of supply chain members of different business activities to come up with final products, services, and information. Indeed, it represents the production, operation activities, physical, knowledge, and financial flows in order to achieve sustainability. Hence, the area of SSCM is very active, and many recent literature reviews deal with quantitative contingency analyses based on dynamic capabilities (Hussain & Malik, 2020; Negri, Cagno, Colicchia, & Sarkis, 2021; Sánchez-Flores, Cruz-Sotelo, Ojeda-Benitez, & Ramírez-Barreto, 2020; Siems, Land, & Seuring, 2021).

Some studies use a qualitative approach, and therefore, there is a need for more analysis in the literature. Thus, some studies apply a systematic literature review methodology by developing a conceptual framework to characterize the aspects, address the issues and contribute to sustainable performance (Mosteanu, Faccia, Ansari, Shamout, & Capitanio, 2020; Vafaeenezhad, Tavakkoli-Moghaddam, & Cheikhrouhou, 2019; Zhang, Yalcin, & Hales, 2020).

Further, other studies establish the SSCM eco-efficient model from a quantitative perspective based on supply chain capability. They consider value co-creation to enhance efficiency and productivity by reducing waste generated from material and human resources (Flores-Sigüenza, Marmolejo-Saucedo, Niembro-Garcia, & Lopez-Sanchez, 2021; Tsai et al., 2021; Tseng, Chen, Wu, & Tan, 2020). Also, environmental issues were considered because they significantly impact efficiency and productivity, such as generated wastes material, human resources GHG emissions, and consumed energy (Sauer & Rebs, 2018; Sharma, Sachdeva, & Singh, 2021; Zeng, Hu, Balezentis, & Streimikiene, 2020).

Finally, some studies classified sustainability from an industry application perspective. Each paper is organized in one industry because each industry has different supply chain network activities and configurations (Vafaeenezhad et al., 2019) used the paper industry. Also, (Islam, Sarker, Hossain, Ali, & Noor, 2020)present SSCM in the Leather industry. (Zare Mehrjerdi & Lotfi, 2019) use car manufacturing, and finally, some papers tackle SSCM from the food industry (Barbosa, 2021; Siems et al., 2021; Wang, Yang, & Qu, 2020).

### 1.6.2 Performance evaluation

Performance evaluation is an important activity in the petroleum industry. It is related to strategic planning to provide feedback on continuous improvement towards this industry's goals. First, economic performance is usually defined as an objective function that maximizes profit, minimized cost, or both (Attia, Ghaithan et Duffuaa, 2019b; Moradinasab *et al.*, 2018a). The economic performance of sustainability represents the cost or profit. Meanwhile, the environment is mainly dominated by reducing $CO_2$ emissions, especially in the petroleum refining sector. (Hadidi et al., 2016). Second, social performance is a significant part that includes the quality of life of the workforce and their families and the local community and society at large (Parast et Adams, 2012).

### 1.6.3 Environment impacts

In this regard, this study's key motivation comes from the significant potential hazards to the environment at different levels. Pollution is the most widespread and dangerous consequence of the petroleum industry (Rebs et al., 2019). It associates with all activities throughout all oil production stages, from exploration to refining that generates wastewaters, gas emissions, and solid waste (Rebs et al., 2019). On the one hand, the petroleum industry's supply chain is one of the most dynamic sectors worldwide. It is essential to emphasize risk assessment in managerial petroleum activities for long-term decisions

### 1.6.4 Marketing diversity (global supply chain)

The marketing of petroleum products is considered the wholesale of petroleum products to business, industry, government, and public consumers. However, several factors can play a significant role in the petroleum industry's marketing, such as price, contract, demand, economic situation, and environmental regulation (Hussain, Assavapokee et Khumawala, 2006). Marketing should care about the current inventory level to manage its sales function.

### 1.6.5 Oil prices

The price of crude oil is an essential factor that affects production and exploration. However, the increase in the price is not always an advantage for this industry where energy consumers can switch to an alternative energy source (less expensive). The example due to the increase of oil price in the last decade reached more than (100$).

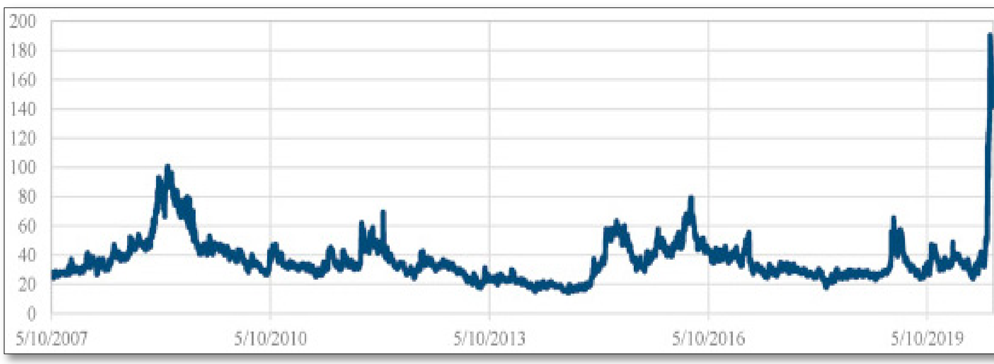



Figure 1.5 Crude oil prices (2007-2020)
Taken from Dutta et.al, (2020)

### 1.6.6 Uncertainties in petroleum supply chain

Uncertainties in petroleum supply chains often make the problem more complicated for short and long-term impacts (Lund et al., 2020). In the short term, it deals with operational variations and equipment failures. On the anther hand, long-term effects the planning process over a long period, such as supply, price, and demand fluctuations. Table 1.1 showed the challenges related to uncertainty for each entity of the supply chain. Therefore, uncertainty is the main factor that impacts decision-making and objectives (Lima et al., 2018). Further, it influences the supply chain's efficiency and performance (Govindan, Fattahi et Keyvanshokooh, 2017).

Table1.1 Challenges related to uncertainty for each entity of the supply chain

| **Supply chain entities** | **Challenges related to uncertainty** | **Decisions** |
|---|---|---|
| Suppliers | ▪ Transportation<br>▪ Human resources<br>▪ Global quality | Tactical<br>Strategic<br>Tactical |
| Production | ▪ Strikes, political issues, natural disasters<br>▪ Selecting the correct raw material.<br>▪ Access to the latest technology.<br>▪ Environmental regulations.<br>▪ Competition from alternative energy.<br>▪ Increased operating costs. | Strategic<br>Strategic<br>Strategic<br>Strategic<br>Tactical<br>Tactical |
| Distributions | ▪ Energy and transportation<br>▪ Critical understanding process | Tactical<br>Strategic |
| Customer | ▪ Price<br>▪ Demand | Strategic<br>Strategic |

The literature review for the published papers in Table 1.2 is related to uncertainty in the petroleum industry. The papers try to tackle the problem from a strategic perspective (planning models with sustainability aspects). Therefore, we will focus on the gaps to understand this uncertainty. However, most studies focus on operational risks such as production risks, loss of demand, and environmental damage. The literature does not provide enough risk sources in a strategic perspective, such as government regulation, the shutdown of some sites, environmental risk, Covid 19, natural disasters. However, we found that most of the papers focus on operational risk.

Table 1.2 Literature review related to the uncertainty petroleum industry

| **Author, Year** | **Planning** | | **Supply chain levels** | | | **Solution method** | **Purpose** | | | | **Operational Risk** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Economic** | | **Environmental** | | |
| | **Strategic** | **Tactical** | **Crude oil** | **Refinery** | **Petrochemical** | | **Min Cost** | **Max Profit** | **Mitigate $CO_2$** | **Others** | |
| (Guillén-Gosálbez et Grossmann, 2010) | ● | ● | - | - | ● | Stochastic non-convex | - | ● | ● | ● | Environmental damage |
| (Ruiz-Femenia et al., 2013) | ● | - | - | - | ● | Stochastic multi-scenario | - | ● | ● | ● | Demand |
| (Al-Sharrah, Lababidi et Ali, 2016) | - | ● | ● | ● | - | Two-stage stochastic | - | ● | ● | - | Environmental production, inventory |
| (Azadeh et al., 2017) | ● | ● | ● | ● | - | Fuzzy unique | - | ● | ● | - | Cost production capacity |
| Current study | ● | ● | ● | ● | ● | MILP | | ● | ● | ● | Environmental risk |

## 1.7 Conclusion

This chapter has covered the background of the petroleum industry, including all the crude oil sectors. It outlines the different factors that affect this industry to provide a solid basis for this research. The knowledge and information adopted were summarized and justified. The next chapter reviews the literature on supply chain, sustainable supply chain planning models in the petroleum industry.

# CHAPTER 2

# RECENT ADVANCES AND OPPORTUNITIES IN PLANNING SUSTAINABLE PETROLEUM SUPPLY CHAINS

## 2.1 Introduction

Supply chain management in the petroleum industry is usually complicated, with a high interconnection between three sectors (Fernandes, Relvas et Paula Barbosa-Póvoa, 2011). The upstream sector is responsible for exploration, drilling, crude oil extraction, and production activities up to the petroleum terminal. The midstream sector covers the transportation (by pipeline, rail, oil tanker or truck, barge), storage, and marketing of crude or refined petroleum products. Finally, the downstream sector covers the remaining activities, such as the production of petrochemicals, distribution activities, wholesale, and marketing (Attia, Ghaithan et Duffuaa, 2019).

Supply chain management (SCM) aims to achieve high revenues while maintaining a high customer satisfaction level and low risks (Levi, Kaminsky et Levi, 2003). SCM in the petroleum sector covers three significant decision stages: strategic, tactical, and operational. Strategic decisions are related to long-term supply chain configuration (candidate-well selection, facility location, capacity allocation, technology selection, and long-term investments) Fernandes, Relvas et Paula Barbosa-Póvoa, (2011). The tactical decisions focus on selecting distribution channels and transportation modes and the product flow through the network and resource allocation (Sahebi, Nickel et Ashayeri, 2014). Finally, the operational decisions cover short-term scheduling activities, such as daily and weekly forecasting, logistics and transportation activity monitoring, and settling of damages or losses with suppliers and customers (Dell et Hart, 2014).

The use of mathematical optimization models to solve SCM problems in the petroleum sector attracts academics and practitioners who step in to improve economic performance. For example, Fernandes, Relvas et Barbosa-Póvoa. (2013) developed MILP to determine the optimal depot locations, capacities, transportation modes, routes, and network design for long-term planning. Kazemi and Szmerekovsky (2015) developed a MILP model for the downstream petroleum supply chain optimization, which minimizes refineries and distribution center costs (Kazemi et Szmerekovsky, 2015). Moradinasab et al. (2018) used a MILP model to optimize a complex network's economic performance, including the upstream and downstream streams (Moradinasab et al., 2018). Jabbarzadeh et al. (2016) proposed a multi-period MILP for offshore crude oil production that maximizes total profit (Jabbarzadeh, Pishvaee et Papi, 2016). Azadeh et al. (2017) proposed MINLP model to design and integrate the upstream and midstream petroleum supply chain to maximize profit (Azadeh et al., 2017).

As it seeks to achieve sustainability, SCM is increasingly considering the environmental and social dimensions while making decisions (Heidary Dahooie et al., 2020; Y. Lakhal, H'Mida et Islam, 2007). Globally, supply chains are facing pressure to green their operations and implement the highest health, safety, and environmental (HSE) protection standards, and this requires planning decisions (Mani, Agrawal et Sharma, 2015; Y. Lakhal, H'Mida et Islam, 2007). Therefore, organizations must evaluate sustainability performance when managing their supply chain to guarantee their business success (Ansari et Kant, 2017; Ferrero-Ferrero, Fernández-Izquierdo et Muñoz-Torres, 2016; Saeed et Kersten, 2020).

The petroleum sector and its different streams (upstream, midstream, and downstream) have seen an increase in adopting sustainable practices as petroleum supply chain activities profoundly affect human health and the environment (Dell et Hart, 2014). A few empirical and model-based research studies have covered the green oil and gas sector (Al-Husain, Assavapokee et Khumawala, 2006; Ansari et Kant, 2017). The literature on sustainable petroleum supply chain planning is still in its infancy and nowhere near the structured nature of other industries such as food, automobile, or manufacturing (Ahmad et al., 2017; Ansari et Kant, 2017). Furthermore, previously published reviews of petroleum supply chain models never explicitly considered the three pillars of sustainability.

Given the importance petroleum holds in many countries and the diversity of sustainability issues in the upstream, midstream, and downstream sectors. A structural analysis is necessary to explore recent developments in mathematical optimization models targeting a solution to SSCM issues in the petroleum industry. To the best of our knowledge, no major review has ever been proposed in this field to analyze the characteristics of planning models developed to operationalize sustainability in the petroleum sector. This study thus synthesizes the literature of sustainable planning models in the petroleum sector from 2010 to 2018. It proposes a classification/taxonomy framework based on different categories to address this knowledge gap and provide future research directions.

The rest of the chapter is organized as follows: Section 2 summarizes the different perspectives of previous literature review efforts in the petroleum sector. The methodology used for this research is explained in section 3. Section 4 discusses the results through descriptive and content analysis. A significant finding analysis regarding SSCM in the petroleum sector, with a discussion on limitations and future research directions, is presented in section 5. Finally, the conclusions of this study are summarized in section 6.

## 2.2 Insights from previous review work

This section provides some specific insights from previous literature reviews. It helps provide relevant background information on the study of petroleum supply chain modelling. Sahebi et al. (2014) present substantive literature on mathematical programming models, focusing on strategic and tactical decisions. However, their effort is limited to the crude sector (Sahebi, Nickel et Ashayeri, 2014). Their study highlights the importance of the total vertical integration of decisions, which helps capture the horizontal integration of the crude petroleum supply chain. They also discuss the importance of including environmental impacts and global factors in the optimization process when designing, planning, and operating the crude sector’s supply chain.

Refinery planning models with strategic, tactical, and operational decisions are discussed in Leiras et al. (2011). The modelling approaches in work are classified based on the different supply chain streams, the modelling type (Linear Programming: LP, Nonlinear Programming: NLP, Mixed Integer Linear Programming: MILP, or Mixed Integer Non-Linear Programming: MINLP), and according to their deterministic or stochastic nature. Lima et al. (2016) review the academic and scientific mathematical programming models for the downstream supply chain (Lima, Relvas et Barbosa-Póvoa, 2016). Their research tries to link academic research with the downstream sector's requirements from a practical perspective. In another study, optimization methods in refineries for a wide range of applications are investigated (Khor et Varvarezos, 2017). The authors provide detailed analysis regarding recent developments of sustainable supply chain planning models at the refinery level. They discuss the techniques and tools used to achieve sustainability from industrial practices and academic research. Nikolopoulou and Ierapetritou (2012) review sustainable supply chain design processes and discuss sustainability from energy efficiency and waste management perspectives (Nikolopoulou et Ierapetritou, 2012).

Schneider et al. (2013) evaluate environmental health issues and safety efforts and progress toward sustainability in the petroleum sector regarding the environmental issue of sustainable development. They identify several gaps in the companies considered in their survey. Indeed, health management and safety management systems still need critical improvements to operationalize the evaluation of supply chain sustainability, focusing on the social dimension (Schneider et al., 2013).

Wan Ahmad et al. (2016) evaluate reports published by 30 companies' practices respecting sustainability, with sustainability forming the evaluation standard. The results show that the reported practices align more with the environmental dimension in most companies than the social dimension. Furthermore, in report guidelines contain no performance indicators for measuring sustainability. Based on these results, an approach for sustainable report practices was developed (Wan Ahmad, de Brito et Tavasszy, 2016). Finally, Fernandes, Barbosa-Póvoa et Relvas, (2011), and Amor et Ghorbel, (2018) discuss the literature on risk management in petroleum supply chains and analyze the challenges and opportunities of research. Table 2.1 outlines the most relevant review papers published in supply chain management in the petroleum industry.

Table 2.1 Previous related literature review

| Reference | Time horizon | Size | Review method | Sector | Specific objective |
|---|---|---|---|---|---|
| (Leiras et al., 2011) | 1991- 2011 | 76 | Keyword search | Refinery | Refineries planning |
| (Fernandes, Barbosa-Póvoa et Relvas, 2011a) | 1992-2011 | 247 | Systematic LR | Integrated | Risk in petroleum supply chains |
| (Nikolopoulou et Ierapetritou, 2012) | 1980- 2012 | 97 | Systematic LR | Petrochemical | Sustainable supply chains in chemical processes |
| (Schneider et al., 2013) | 2001-2013 | 35 | Keyword search | Integrated | Sustainability petroleum industry |
| (Sahebi, Nickel et Ashayeri, 2014b) | 1988-2013 | 93 | Keyword search | Crude oil | Planning models within the crude oil |
| (Wan Ahmad, de Brito et Tavasszy, 2016) | 2003-2015 | 48 | Keyword search | Integrated | Corporate sustainability practices |
| (Lima, Relvas et Barbosa-Póvoa, 2016) | 1996-2015 | 81 | Keyword search | Refinery | Downstream petroleum supply design |
| (Khor et Varvarezos, 2017) | 1979-2015 | 173 | Keyword search | Refinery | Petroleum refineries planning |
| (Amor et Ghorbel, 2018) | 1972-2017 | 127 | Keyword search | Integrated | Risk in the petroleum supply chain |

Despite articles about supply chain management in the petroleum sector, none were to be demonstrated found to have carried out a comprehensive review of planning models integrating the three sustainability dimensions. The integration of the different decision levels and the various stages (upstream, midstream, downstream) is also a topic of interest currently neglected in the literature.

This study thus tries to fill the above gaps by using an (SLR) methodology of articles, with a primary focus on developing planning models that include at least two of the three sustainability dimensions (economic, environmental, social). Furthermore, the SLR aims to analyze relevant papers extracted following a systematic material collection, identify recent advances, and define new research opportunities in the area of sustainable petroleum supply chain planning. To achieve the main objective, the study provides answers to the following research questions:

- What is the current research status in SSCM in the petroleum sector?
- What are the main characteristics of mathematical optimization models and the solutions approach used in current research to implement sustainability?
- What are the main SCM decisions considered, and which performance criteria are considered in evaluating the supply chain?
- What are the research opportunities that can be addressed in the future?

### 2.3 Research methodology

The research methodology consists of a structured review covering sustainable supply chain planning models in petroleum industry research. It starts by identifying keywords based on which papers are selected by using the citation method (Pittaway et al., 2004). SLR is a valuable tool that can help the researcher comprehend diversity in terms of knowledge and historic development regarding a specific research topic. Moreover, a literature review helps the researcher identify further research opportunities by analyzing research gaps in the existent body of knowledge. The systematic content analysis process selected to develop the required methodology of this work consists of the following steps (Junior et Godinho Filho, 2010; Krippendorff, 1980): material collection, descriptive analysis, category selection, material evaluation.

#### 2.3.1 Material collection and descriptive analysis

This research presents a (SRL) of sustainable supply chain planning models in the petroleum industry, with a specific focus on strategic and tactical decisions. After the topic selection, a first search was carried out to investigate the latest published scientific papers using publishing databases such as Web of Science, Scopus, and Google Scholar. The papers were selected based on their full coverage of selected keywords. Examples included “supply chain planning,” or” mathematical modeling,” “sustainable, “or “emission” or “GHG,” and “Petroleum” or “Oil and Gas.” The papers were filtered according to essential criteria such as the use of the English language, the inclusion of a mathematical model for planning (strategic and tactical decisions), and a minimum of two sustainability dimensions in the objective. The search for published papers covered the 2010 to 2019 period.

At this step, we collected 450 papers from different databases. We selected only papers that developed mathematical programming models and kept those focusing on environmental sustainability in the supply chain context. Further, the remaining articles we selected were those that considered strategic and tactical decisions. Meanwhile, we excluded papers using a qualitative research methodology, duplicate papers, studies focusing only on the economic dimension, and articles considering operational decisions.

At the end of the process, twenty-three (23) papers meeting the criteria of this study were selected. However, it should be noted that the excluded papers still contain useful information that could be valuable for other studies. An initial descriptive analysis was prepared for the selected papers according to the publication periods and the origin of the study (journal or conference).

### 2.3.2 Category selection

*Supply chain structure*, *modelling*, and *sustainability evaluation* were the main research focus areas. They were defined as the structural dimensions corresponding to the research questions of this study. Table 2.2 shows the classification scheme of the analytical models and the structure content analysis. The critical dimensions of the sustainable supply chain are the supply chain structure, the decision level, the modelling approach, and shared information (Huang, Lau et Mak, 2003; Mula et al., 2010). Solution techniques, environmental impacts, purpose, and limitations are essential criteria to be considered in performing supply chain analysis.

Table 2.2 Classification scheme of analytical models

| Structural dimension | Analytic categories |
|---|---|
| *Supply chain structure* | |
| 1. Supply chain level | Crude, Refinery, Petrochemical, and Transportation |
| 2. Planning decision phase | Strategic and Tactical |
| *Modeling dimensions* | |
| 3. Modeling approach | Tools and solvers, Time horizon, Number of periods, and Case studies |
| 4. Model purpose | Economic and environmental |
| 5. Decisions | |
| *Sustainability evaluation* | |
| 6. Two dimensions | Economic and environmental |

### 2.3.3 Material evaluation

Each paper's content was analyzed according to the established structural dimensions and analytic categories to achieve the research goals. Figure 2.1 provides a detailed description of the steps, including feedback obtained following revisions of the analysis of the collected material. The material evaluation was based on the data collection and structure dimension at any given stage. Further, the paper's structure was developed based on the recent development trends in the petroleum industry and sustainable supply chain.

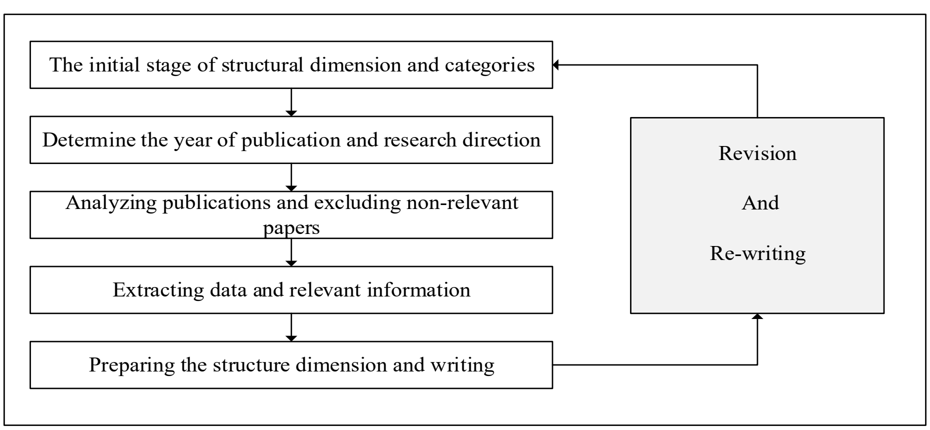



Figure 2.1 Research methodology steps

## 2.4 Results

The sustainable supply chain modeling process is a new and increasingly common research discipline, especially in the petroleum industry Y. Lakhal, H'Mida et Islam, (2007). Since 2010, the number of articles developing sustainable supply chain models has grown significantly (+ 65%) compared to the number of published papers in this area during the 80s and the 90s. The process's strong growth is illustrated by the temporal distribution of the present study’s sample of 23 papers. Next, we will discuss the selected papers’ descriptive analysis based on the categorization framework explained in Table 2.1.

### 2.4.1 Descriptive analysis

The distribution of the selected papers published between 2010-2019, which focuses on sustainable petroleum supply chain planning, is shown in Figure 2.2. In the exact figure, we also added the distribution of papers focusing on strategic and tactical mathematical models for the petroleum supply chain published between 1988 and 2013 and obtained from the study of Sahebi et al. (2014). We also extracted the frequency distribution of papers published between 1988 and 2013 that focus on sustainability.

It is clear from the results that research in developing mathematical models for sustainable planning for the 1998-2009 period (7 papers) is still in its infancy during that time frame. From 2010 to 2014, a considerable increase is observed, with 14 papers published, which contribute to 50% of the total number of articles published in the area between 1988 and 2019 (30 years). This increase is linked to the rise of environmental and social awareness in many sectors and to the critical role supply chain management plays in solving problems Ansari et Kant (2017). It is interesting to note that this research effort is correlated with the increase in oil prices during the same period (2010-2014). Moreover, figure 2.2 shows that in 2016 and 2017, the number of papers in this field increases to three for each year, while in 2018, a single paper was published, and two in 2019.

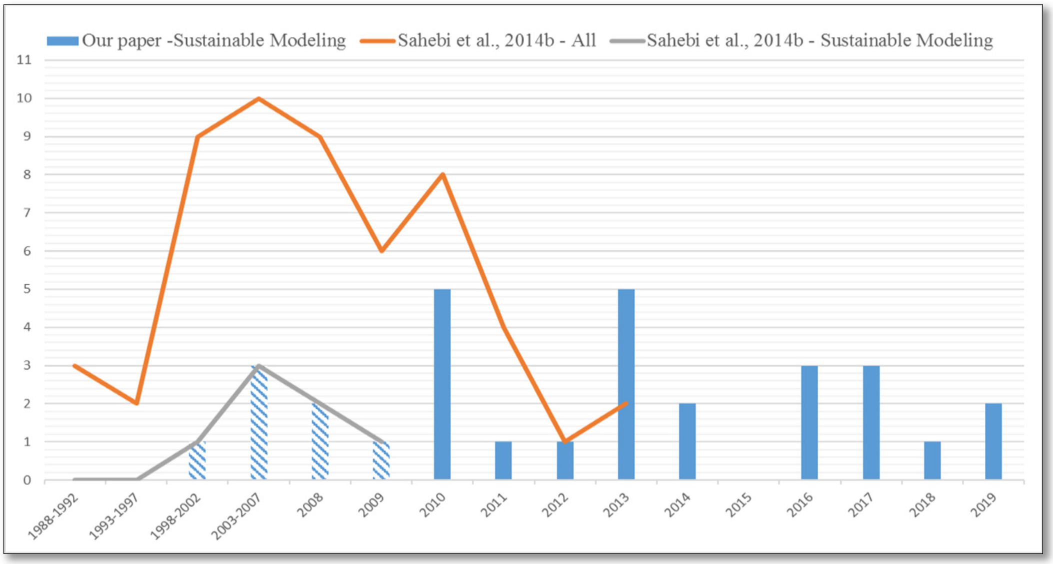
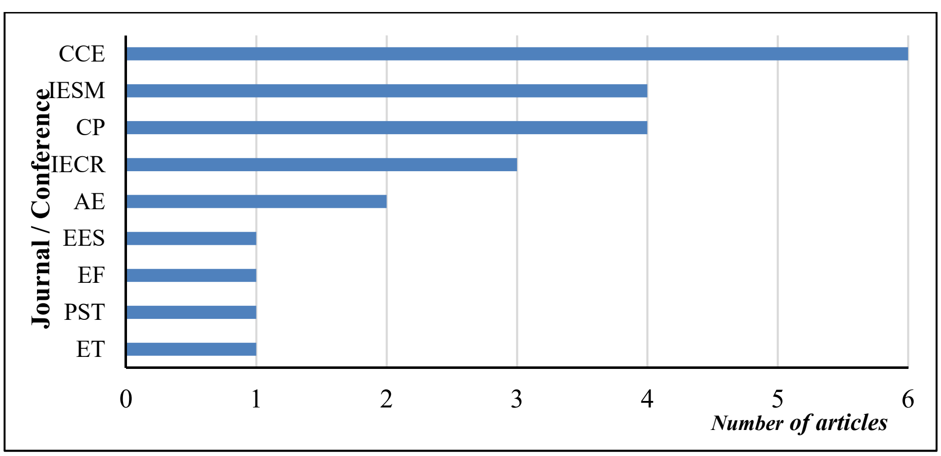



Figure 2.2 Distribution of the reviewed papers according to the publication year

The 23 papers selected in this study have been published across nine journals and conferences, as presented in Figure 2.3. The Journal of Computers & Chemical Engineering is the leading journal in this area, with the highest number of papers published (6 in all). We also notice the limited number of journals/conferences where authors can publish in this area.




**CCE**: Journal of Computers & Chemical Engineering
**JCP**: Journal of Cleaner Production
**AE**: Journal of Applied Energy
**EF**: Journal of Energy & Fuels
**ET**: Journal of Engineering and Technology
**PST**: Journal of Petroleum Science and Technology
**IECR**: Journal of Industrial & Engineering Chemistry Research
**EES**: Earth and Environmental Science (Conference)
**IESM**: Industrial Engineering and Systems Management (Conference)

Figure 2.3 Distribution of reviewed papers by source

### 2.4.2 Content analysis

In this section, different criteria analyses are presented. The critical criteria for the analysis of sustainable supply chains focus on critical factors such as the purpose of each study, the supply chain structure, the decision level, the modeling approach, and the performance evaluation indicators used for each study (Huang, Lau et Mak, 2003; Mula et al., 2010; Sahebi, Nickel et Ashayeri, 2014).

- **Purpose of the study**

The purpose of a supply chain model can be driven by qualitative and/or quantitative performance measures. Although some aspects of qualitative objectives may be quantified, there is no single direct numerical approach used for measurement (Beamon, 1998). Table 2.3 highlights the purpose of the selected reviewed papers. From an economic perspective, profit maximization is the main objective for most papers (Ruiz-Femenia et al., 2013; Al Dhaheri et Diabat, 2010). Minimization of the total cost is not the typical approach when sustainability is considered in the supply chain planning model since the objective is to identify the decisions needed to maximize value from a possible collaboration between supply chain partners in terms of the environment and the social impact (Alnifro et al., 2017). However, Khor et Elkamel. (2010) investigate both revenues maximization and cost minimization simultaneously.

We can also observe that all the selected papers include the environmental dimension. Carbon dioxide ($CO_2$) mitigation/reduction is defined as the primary environmental objective. It is mainly explained by the fact that $CO_2$ emissions represent more than 80% of all emissions, especially from refineries (Elkamel et al., 2008). However, regarding environmental impacts, there are many other issues than just $CO_2$ emissions that are very significant and need to be included in the petroleum sector due to their impact on sustainability. Crude oil spills, water contamination, solid waste from the operation process, and transportation activities are some examples of potential environmental problems created by the petroleum industry (Azadeh et al., 2017; Yuan et al., 2019). Also, three studies consider the specific emissions of Carbon dioxide ($CO_2$), Sulfur Dioxide ($SO_2$), and Nitrogen Oxide (NOx) (Azadeh et al., 2017; Hadidi et al., 2016; Yuan et al., 2019).

Table 2.3 Purpose of the selected reviewed papers

| **Papers** | **Purpose** | | | | |
|---|---|---|---|---|---|
| | | **Economic** | | **Environmental** | |
| | | Min Cost | Max Profit | Mitigate $CO_2$ | Other |
| (Guillén-Gosálbez et Grossmann, 2010) | Design sustainable chemicals to evaluate environmental performance | | ● | | ● |
| (Al Dhaheri et Diabat, 2010) | Evaluate different options for reducing $CO_2$ emissions at refineries | | ● | ● | |
| (Ba-Shammakh, 2010) | Min technology cost for emissions control | | ● | | ● |
| (Khor et Elkamel, 2010) | investment to minimize the environmental risk using Life cycle assessment (LCA) | | ● | | ● |
| (Al-Sharrah, Elkamel et Almanssoor, 2010) | sustainable planning for environmental, economic safety objectives | | ● | | ● |
| (Liu et al., 2011) | Capture planning strategy, logistical and technical options | | ● | ● | |
| (Ruiz-Femenia et al., 2012) | Design a chemical SC to minimize environmental impact by using the LCA | | ● | ● | ● |
| (Ruiz-Femenia et al., 2013) | Reduce $CO_2$ and $SO_2$ pollutants in oil refineries by taking cap and trade | | ● | ● | ● |
| (Gezehei et Almehrezi, 2013) | Reduce $CO_2$ emissions in Fluid catalytic cracking (FCC) at refinery unit | | ● | ● | |
| (Kangas, Nikolopoulou et Attiya, 2013) | Support optimal $CO_2$ reduction strategies | | ● | ● | ● |
| (Alhajri et al., 2013) | Maximize profit reduce $CO_2$ emissions | | ● | ● | |
| (Liu, Kayyali et Yousef, 2013) | Develop economic pipeline network with less environmental impact | | ● | ● | |
| (Sahebi, Nickel et Ashayeri, 2014) | Increase refinery margin and reduce economic losses due to energy waste | ● | ● | ● | |
| (Zhao, Rong et Feng, 2014) | Optimize SC by introducing sustainability factors | | ● | ● | |
| (Al-Sharrah, Lababidi et Ali, 2016) | Perform $CO_2$ mitigation for offshore oil | ● | ● | ● | |
| (Nguyen et al., 2016) | Control and mitigate emissions in refineries (NOx, Sox, and VOC). | | ● | ● | |
| (Hadidi et al., 2016) | Develop and transform oilfield planning via green aspects | | ● | ● | |
| (Azadeh et al., 2017) | Reduce GHG emissions in transporting crude oil products | | ● | ● | |
| (Moretti et al., 2017) | Determine optimal production planning oil refinery while reducing GHG emission | | ● | ● | |
| (Alnifro et al., 2017) | Maximize profit and minimize pollution by facilities and transportation modes | | ● | ● | ● |
| (Moradinasab et al., 2018) | Design sustainable chemical SC and evaluate the environmental performance | ● | ● | ● | |
| (Attia, Ghaithan et Duffuaa, 2019) | Optimize sustainability and supply chain | ● | ● | ● | |
| (Yuan et al., 2019) | Mitigate emissions | ● | | ● | ● |

- **Categorizing the reviewed papers based on the supply chain structure**

As earlier stated, the supply chain structure in the petroleum industry has three major segments: upstream, midstream, and downstream. Figure 2.4 represents the different facility nodes considered in the mathematical models. Again, it is clear that the primary focus is on refineries. Indeed, 15 out of the 23 papers integrate refinery facilities when developing the sustainable supply chain planning model. In some cases, refineries are integrated into nearby petrochemical plants Zhao et al., (2017). " The petrochemical plants produce high-value products such as ethylene, acetone, propylene, styrene, phenol, butadiene, and benzene" (Al-Othman et al., 2008b; Ruiz-Femenia et al., 2013). Only a few studies tried to propose supply chain decision mechanisms to achieve sustainability at the upstream (crude oil production) and petrochemical plants.

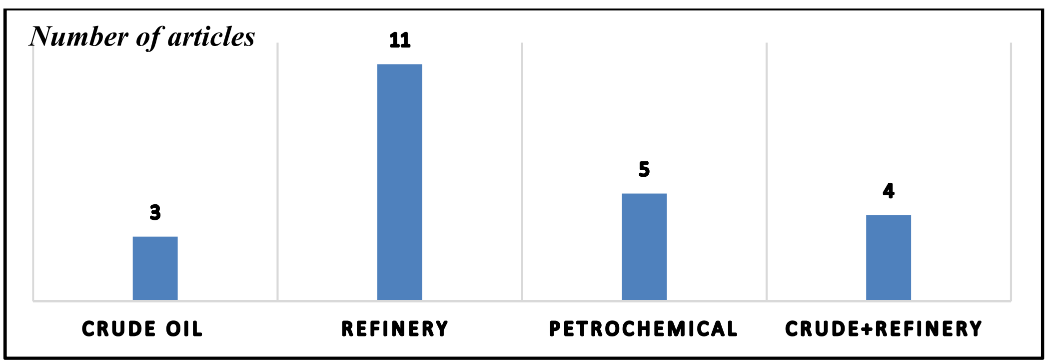



Figure 2.4 Petroleum supply chain structure

Transportation of crude oil is a part of the midstream sector. It represents a significant expense compared to other industries MirHassani (2008). The transportation system connects the nodes and ensures product flow between wells, refineries, petrochemical plants, and customers. The transportation modes that are generally used in the petroleum industry are pipelines, railways, and petroleum boats. Regarding each mode is used, the main environmental impact of transportation is GHG emissions and oil spills, which seriously threaten the environment.

Therefore, some researchers have considered the environmental impacts of transportation activities on the petroleum supply chain (Kutz et Elkamel, 2010; Yuan et al., 2019). An integrated model, in which transportation decisions are also considered in strategic and tactical planning of a sustainable supply chain, could modify the network structure and the transportation cost structure.

Here, it could considerably reduce the environmental risks without reducing profits (Yuan et al., 2019). Moradinasab N et al. (2018) designed an approach to minimize the amount of environmental pollution generated by transportation modes for the downstream supply chain (Moradinasab et al., 2018). Sahebi, Nickel et Ashayeri, (2014) Introduced a mathematical model to design the upstream petroleum supply chain for petroleum field development and crude oil transportation by a pipeline network (Sahebi, Nickel et Ashayeri, 2014).

As for a holistic view of the supply chain, where the three levels (crude oil, refinery, and petrochemical) are integrated (Al-Othman et al., 2008). This highlights a significant need for further research that considers a multi-level supply chain and a systemic view of the petroleum supply chain to efficiently plan sustainable supply chains and different decision phases. The integration of the various sectors increases the model's complexity but would be useful to find a holistic strategy to achieve sustainability at the country level.

- **Categorizing the reviewed papers based on the decision phase**

In general, supply chain decisions are different based on the range of activities considered, and primarily horizontal or vertical. The horizontal level focuses on the supply chain structure, while, for its part, the vertical level describes the decision levels (Sahebi, Nickel et Ashayeri, 2014). Based on the results obtained (see Table 3), the strategic decisions will cover facility location, flow allocation and capacity sizing, technology selection, transportation modes, outsourcing, and investments. Strategic decisions have a long-term impact on the supply chain due to its positioning on its market., which involves facilities and resources (Sahebi, 2013). However, tactical decisions focus on production, distribution and resource planning, inventory management, and control policies, where the time horizon is usually comprised between a month and a year (Attia, Ghaithan et Duffuaa, 2019b; Jabbarzadeh, Pishvaee et Papi, 2016) (see Table 2.4).

Some previous studies showed the benefits of integrating strategic and tactical decisions in the same model to identify the optimal infrastructure network and production levels, distribution, and storage resources to satisfy the market demand cost-effectively (Papageorgiou, 2009). Furthermore, Barbosa-Póvoa, (2014). stated that the results improve whenever both strategic and tactical decisions are simultaneously considered in any sustainable supply chain network. Thus, it is essential to simultaneously consider strategic and tactical decision integration for long-term sustainable strategy implementation.

Table 2.4 Distribution of reviewed papers based on decision levels

| **Papers** | **Decisions** | | **Supply chain levels** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Crude oil** | | **Refinery** | **Petrochemical** | **Transportation** | | | |
| | **Strategic** | **Tactical** | **Onshore** | **Offshore** | | | **Pipelines** | **Maritime** | **Railway** | **roads** |
| (Guillén-Gosálbez et Grossmann, 2010) | ● | ● | | | | ● | | | | |
| (Al Dhaheri et Diabat, 2010) | ● | | | | ● | | | | | |
| (Ba-Shammakh, 2010) | | ● | | | ● | | | | | |
| (Khor et Elkamel, 2010) | | ● | | | ● | | | | | |
| (Al-Sharrah, Elkamel et Almanssoor, 2010) | ● | ● | | | | ● | | | | |
| (Liu et al., 2011) | ● | ● | | | | ● | | | | |
| (Ruiz-Femenia et al., 2012) | ● | ● | | | | ● | | | | |
| (Ruiz-Femenia et al., 2013) | ● | | | | | ● | | | | ● |
| (Gezehei et Almehrezi, 2013) | ● | | | | ● | | | | | |
| (Kangas, Nikolopoulou et Attiya, 2013) | | ● | | | ● | | | | | |
| (Alhajri et al., 2013) | ● | ● | | | ● | | | | | |
| (Liu, Kayyali et Yousef, 2013b) | ● | ● | | | ● | | | | | |
| (Sahebi, Nickel et Ashayeri, 2014) | ● | ● | ● | | | | ● | ● | | |
| (Zhao, Rong et Feng, 2014) | ● | ● | | | ● | | ● | | | |
| (Al-Sharrah, Lababidi et Ali, 2016) | | ● | ● | | ● | | ● | | | |
| (Nguyen et al., 2016) | ● | | | ● | | | ● | ● | | |
| (Hadidi et al., 2016) | ● | ● | | | ● | | ● | | | |
| (Azadeh et al., 2017) | ● | ● | | ● | ● | | ● | | | |
| (Moretti et al., 2017) | ● | | | ● | ● | | ● | | | |
| (Alnifro et al., 2017) | ● | ● | | | ● | | | | | |
| (Moradinasab et al., 2018) | ● | ● | ● | | ● | | ● | | ● | |
| (Attia, Ghaithan et Duffuaa, 2019) | | ● | | ● | | | | | | |
| (Yuan et al., 2019) | | ● | | | ● | | ● | ● | ● | ● |

Among the twenty-three (23) reviewed papers, twelve (12) consider strategical and tactical decisions simultaneously (Guillén-Gosálbez et Grossmann, 2010; Liu et al., 2011; Sahebi, Nickel et Ashayeri, 2014; Zhao, Rong et Feng, 2014). Five (5) papers considered only strategic decisions, while three (6) studies focused only on tactical decisions. Moradinasab et al. (2018)

developed a Mixed-integer linear programming (MILP) model that integrates the crude oil and refinery sectors.

The study considered the economic decisions (flow rate, capture technology, inventory management, the fulfilment of demand quantities) and environmental decisions (capture technology, transportation mode selection (see Tables 2.5 and 2.6). On the other hand, Moretti et al. (2017) used economic decisions (production quantity and refined capacities) along with environmental decisions (transportation modes ~ see Table 4) in developing the Mixed-integer Non-linear programming (MINLP) to integrate the crude oil and refinery in the same model. The economic decisions (facility allocation, extraction technology, transportation, distribution, oilfield development planning, and production quantity) and the environmental decisions (extraction technology and crude oil leakage and emissions through transportation) were implemented using a MILP modelling methodology (Azadeh et al., 2017; Yuan et al., 2019).

Table 2.5 Distribution of reviewed papers based on decision type

| **Decisions** | | **Papers** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (Guillén-Gosálbez et Grossmann, 2010) | (Al Dhaheri et Diabat, 2010) | (Ba-Shammakh, 2010) | (Khor et Elkamel, 2010b) | (Al-Sharrah, Elkamel et Almanssoor, 2010) | (Liu et al., 2011) | (Ruiz-Femenia et al., 2012) | (Ruiz-Femenia et al., 2013) | (Gezehei et Almehrezi, 2013b) | (Kangas, Nikolopoulou et Attiya, 2013b) | (Alhajri et al., 2013) |
| **Economic-oriented decisions** | Facility location | | | | | • | | | • | | | • |
| | Facility allocation | | | | • | | | | | | | |
| | Product flows | • | • | • | • | • | • | • | • | • | • | • |
| | Transportation mode selection | | | | | | | | • | | | |
| | Inventory planning | • | | | | | | • | • | • | | |
| | Production quantity | • | • | | | • | | • | • | | • | |
| | Fulfillment of demand | | • | | | • | • | | • | | • | • |
| | Product price | | | | | | | | | | • | |
| | Storage tanks capacity | • | | | | | | | | • | | |
| **Environmental oriented decisions** | Technology selection | • | • | • | | | • | • | • | • | | • |
| | Transportation mode selection | • | | | | | | | | | | |
| | Capture technology | | • | • | | | • | • | | • | | • |
| | Implementation of waste heat Recovery | | | | • | | | | | | | |
| | Emissions flow rate | | • | • | | | | • | • | • | | • |
| | Hazardous effect | | | | | • | | | | | | |

Table 2.6 Distribution of reviewed papers based on decision type (continued)

| Decisions | | Papers | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (Liu, Kayyali et Yousef, 2013b) | (Sahebi, Nickel et Ashayeri, 2014a) | (Zhao, Rong et Feng, 2014) | (Al-Sharrah, Lababidi et Ali, 2016a) | (Nguyen et al., 2016) | (Hadidi et al., 2016) | (Azadeh et al., 2017a) | (Moretti et al., 2017) | (Moradin asab et al., 2018a) | (Alnifro et al., 2017a) | (Attia, Ghaithan et Duffuaa, 2019b) | (Yuan et al., 2019) |
| **Economic oriented decisions** | Facility location | • | • | • | | • | | • | | | | | |
| | Facility allocation | | • | | | | | • | | | | | |
| | Product flows | | • | | | | | • | | | | | |
| | Transportation mode selection | | • | | | | | • | | | | | |
| | Inventory planning | • | • | • | • | • | • | | | • | • | • | • |
| | Production quantity | | • | | • | | | | | | | | • |
| | Fulfillment of demand | | | • | | | • | | • | • | | | |
| | Product price | • | | • | | | | • | • | | • | • | • |
| | Storage tanks capacity | | | • | • | | | | | • | • | • | • |
| | Technology selection | | | | | | | | | | | • | |
| | Transportation mode selection. | | | | | | | | | | • | | |
| **Environmental oriented** | Technology selection | • | • | • | | • | • | • | | | • | | |
| | Transportation mode selection | | | • | | • | | • | • | • | | | • |
| | Capture technology | | | | | | | • | | | | | • |
| | Implementation of waste heat Recovery | • | | | | | | | | • | • | | |
| | Emissions flow rate | | | | | • | | | | | | | |
| | Hazardous effect | • | | | | | • | • | | • | | • | • |
| | Technology selection | | | | | | | • | | • | | | • |

- **Categorizing the reviewed papers based on the modelling approach**

The modelling approach is determined based on inputs, statements, and objectives. Table 5 represents the classification results. Models are classified based on three categories. The first is the linear programming approach. Particularly, the MILP is the most common methodology used in sustainable supply chain planning for different petroleum sectors Hadidi et al., (2016). Of the twenty-three (23) papers used in this study, thirteen (13) proposed MILP models. Conversely, for the second approach, MINLP, eight (8) papers used this type Guillén-Gosálbez et Grossmann, (2010); Zhao, Rong et Feng, (2014).

The third approach is multi-objective modelling, with seventeen (17) papers referring to the modelling approach. The models that integrate economic and environmental objectives involve linear or nonlinear multi-objective programming. Some studies maximize profit Sahebi, Nickel et Ashayeri, (2014), while others minimize the total cost (Alnifro et al., 2017; Khor et Elkamel, 2010). On the other hand, the second objective tries to minimize environmental threats: emissions, wastewater, and crude oil leakage through transportation. Furthermore, Moradinasab et al., (2018) develop a model to maximize profits and minimize the emission of $CO_2$ and other GHG coming from various transportation modes (see Table 2.7).

Strategic and tactical decisions in the context of the petroleum supply chain seek to establish long-term strategies and policies in the network. For instance, Al-Sharrah, Elkamel et Almanssoor, (2010) addresses a 20-year time horizon. Al Dhaheri et Diabat, (2010) use a 14-year time horizon to incorporate crude price variability and demand forecasts. Azadeh et al., (2017) consider a planning period of 15 years and discretize them into six months to improve the economy and environment simultaneously. Liu et al. (2011) consider a 30-year investment time horizon and divide the medium time into six periods of five years Liu et al.,( 2011), while

Sahebi, Nickel et Ashayeri, (2014) assume 14 one-year planning periods to test the proposed model.
From an application perspective, different real-life examples from different countries have demonstrated the benefits of sustainability in the petroleum sector. Furthermore, case studies describe the status of relevant recent development features, detailing insights on rules, existing challenges, and potential future changes in long-term planning in the petroleum sector for different countries. However, three triggers for sustainable supply chain management push the decision-maker to use such models Seuring et Müller, (2008) solving the problem, supply chain management as a tool to comply with new regulations, and balancing economic and environmental (Eco-efficiency).

Usually, environmental regulation comes with different rules that apply in a specific country and relative to each industrial sector. The reviewed papers mention that the implemented case studies are based on new legislation that tries to respect the Kyoto protocol's climate change rules and global warming in order to address international concerns. These regulations pushed the petroleum sector to address the environmental aspect through its supply chain. For instance, case studies from European countries (Germany, Spain, UK, and the Netherlands) followed effectively with a reduction in energy consumption Yuan et al., (2019). Environmental regulations in the Gulf countries, especially Saudi Arabia, are other examples where the refinery industry has tried to evaluate voluntary mechanisms to minimize GHG and produce a product such as gasoline, jet fuel, and clean diesel. These studies show that environmental protection planning targets a safer operation with economic gain (Al-Sharrah, Elkamel et Almanssoor, 2010; Ba-Shammakh, 2010; Hadidi et al., 2016).

Generally, the Eco-efficiency perspective is used to improve economic and environmental outcomes simultaneously by measuring the global warming potential of each chemical released from different processes. Stakeholders have encouraged developments using more energy-efficient and environmentally friendly solutions employing new technologies for extraction, production, and storage while abiding by OPEC's crude oil quota limitations. Moreover, emission reductions allow different stakeholders, companies, and plants to meet their obligations by producing clean products Zhao, Rong et Feng, (2014); Kangas, Nikolopoulou et Attiya, (2013).

Table 2.7 Classification of reviewed papers based on modeling approach

| Papers | Model type | Multi-objective | Solvers | Periods | Case study | Country |
|---|---|---|---|---|---|---|
| (Guillén-Gosálbez et Grossmann, 2010) | MINLP | ● | SBB | 3 years | Numerical case study | Spain, Germany, Portugal |
| (Al Dhaheri et Diabat, 2010) | MINLP | ● | BARON | 20 years | Complex refinery 85,000 b/day | Abu Dhabi refinery |
| (Ba-Shammakh, 2010) | MINLP | ● | SBB | 1 year | Real Refinery 100 000 bbl./day | Saudi Arabia |
| (Khor et Elkamel, 2010) | MILP | ● | CPLEX | 1 year | A refinery on a numerical example | Not specified |
| (Al-Sharrah, Elkamel et Almanssoor, 2010) | MILP | ● | CPLEX | 20 years | petrochemical network industry | Kuwait |
| (Liu et al., 2011) | MILP | - | CPLEX | 30 years | Real-life case study | United Kingdom, England |
| (Ruiz-Femenia et al., 2013) | MILP | - | CPLEX | 3 years | Real case study | Spain, Germany, Portugal |
| (Gezehei et Almehrezi, 2013) | MILP | ● | Not specified | Not specified | Numerical case study | Abu Dhabi |
| (Kangas, Nikolopoulou et Attiya, 2013) | MINLP | ● | Not specified | Not specified | Numerical case study | United Arab Emirates |
| (Alhajri et al., 2013) | MINLP | ● | SBB | Not specified | Numerical case study | Not specified |
| (Liu, Kayyali et Yousef, 2013b) | MINLP | ● | Not specified | Not specified | Numerical case study | Not specified |
| (Sahebi, Nickel et Ashayeri, 2014) | MILP | ● | CPLEX | 14 years | Persian Gulf case study | Iran |
| (Zhao, Rong et Feng, 2014) | MINLP | ● | CPLEX | 8 years | Refinery and Utility System | China |
| (Al-Sharrah, Lababidi et Ali, 2016) | MILP | ● | CPLEX | 1 year | Refinery & Petrochemicals | Kuwait |
| (Nguyen et al., 2016) | MILP | ● | Not specified | 30 years | Upstream Crude Oil Offshore | Scotland |
| (Hadidi et al., 2016) | MILP | ● | BARON | 1 year | Refinery capacity 31796 b/d | Saudi Arabia |
| (Azadeh et al., 2017) | MILP | ● | Matlab | 10years | Platforms, wells, and refineries | Persian Gulf |
| (Moretti et al., 2017) | MINLP | ● | Not specified | 4 years | Real case study | Belgium |
| (Alnifro et al., 2017) | MILP | | Not specified | 7 years | Refinery feed 100,000 b /d | United Arab Emirates |
| (Moradinasab et al., 2018a) | MILP | ● | Matlab | Not specified | Real case study | Iran |
| (Attia, Ghaithan et Duffuaa, 2019) | - | ● | CPLEX | 1 year | Real case study | Saudi Arabia |
| (Yuan et al., 2019) | MILP | | Mat lab | 1 year | Crude Oil network | China |

Using a different perspective for solving the petroleum sector's environmental problems, many case studies investigate how to model GHG emissions from the supply chain perspective and focus on streams responsible for significant emissions Gezehei et al. mehrezi, (2013).

Furthermore, they study different mitigation alternatives for GHG emissions reduction associated with different investment costs  Hadidi et al., (2016).  Sahebi, Nickel et Ashayeri, (2014) present a methodology to compare different available technologies for extraction, production, and storage processes regarding environmental and economic performance.

- **Categorizing the reviewed papers based on environmental problem**

The petroleum industry can be very harmful to the environment in different ways, mainly through contamination of the air, water, and soil, and consequently, to all the living beings on our planet  Mariano et La Rovere (2017). Massive pollution is a serious consequence of activities of the different stages of petroleum production, exploration, and refining. Figure 2.5 shows that wastewater, gas emissions, and solid waste generated during drilling, production, refining, and petrochemicals production are among the most significant polluters sector van Straelen et al., (2010).

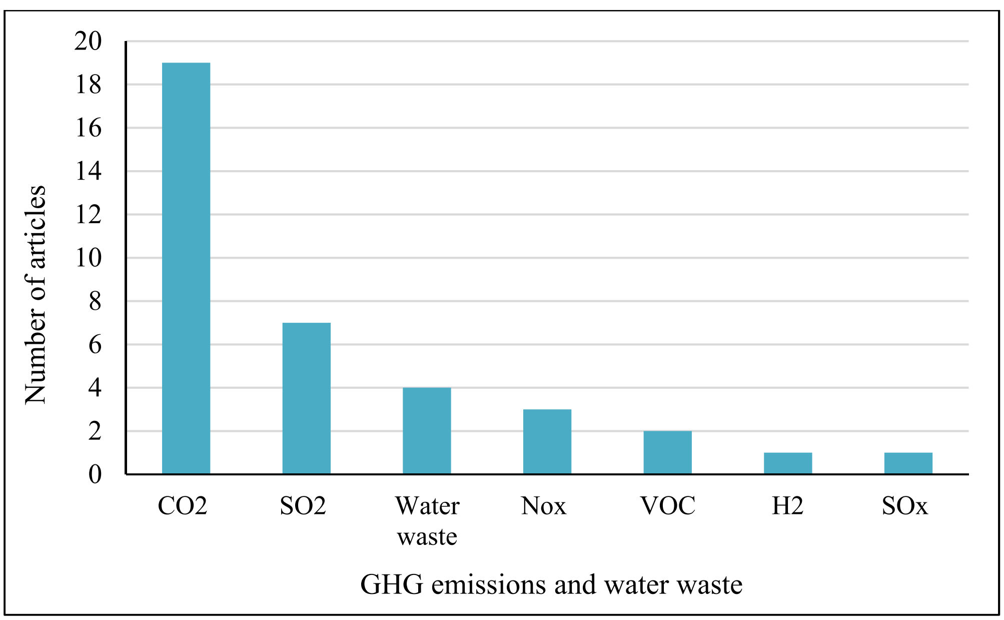



Figure 2.5 Emissions from petroleum supply chain activities adapted

In 2014, the U.S. Environmental Protection Agency (EPA)'s annual report stated that $CO_2$ emissions account for 97% of GHG produced by refineries in the US. Therefore, considering the environmental dimension in production processes has been a serious and significant challenge for the petroleum industry. Today, providing sustainable development beyond ethical and moral obligations is demanded by society. In Table 2.8, we notice that GHG emissions mitigations are preponderant in most of the reviewed papers. For example, Nguyen et al. (2016) investigate $CO_2$ and $CH_4$ mitigations at the crude oil sector level. The technology used to mitigate GHG is a sea injection, where the captured gas is injected through the pipeline into the deep sea. Also, most of the reviewed studies focused specifically on $CO_2$ mitigations at the refinery level (Figure 2.6).

Zhao, Rong et Feng, (2014) investigate the capture of $CO_2$ and $SO_2$ emissions in the blending process at the refinery level. They propose incorporating $CO_2$ and $SO_2$ emission factors into the blending process to study how to increase or decrease boilers' efficiency, which significantly affects GHG emissions. Moradinasab et al. (2018) study the integration of $CO_2$ and solid waste reduction at the crude production level and $CO_2$ and $SO_2$ reduction at the refinery level. Also, Al-Sharrah, Lababidi et al. (2016) study the capture of $CO_2$ emissions at the three levels. Hadidi et al. (2016) investigate strategies to reduce the Nitrogen oxides (NOx), Sulphur oxides (SOx), and Volatile Organic Compounds (VOC) only at the refinery level. Finally, Azadeh et al. (2017) mitigate $CO_2$ and waste at the crude level. At the refinery level, the three primary emissions are Carbon dioxide ($CO_2$), Sulfur Dioxide ($SO_2$), and Nitrogen Oxides (NOx).

Only two studies published by Moradinasab et al. (2018) and Sahebi, Nickel et Ashayeri, (2014) investigate GHG emissions in transportation. On the other hand, Azadeh et al. (2017) consider three environmental issues to minimize the environmental impact, emissions, wastewater, and crude oil leakage through transportation. The Life Cycle Assessment (LCA) methodology is used to evaluate the environmental performance (Azadeh et al., 2017; Guillén-Gosálbez et Grossmann, 2010; Sahebi, Nickel et Ashayeri, 2014).

Table 2.8 Classification of papers based on the environmental problem

| **Supply Chain levels** | **Environmental evaluation/ Measurement** | **Technology selected (solution)** | **Articles** |
|---|---|---|---|
| Crude | $CO_2$ | Transport optimization | (Al-Sharrah, Lababidi et Ali, 2016); (Azadeh et al., 2017; Moradinasab et al., 2018) |
| | | $CO_2$ injected into the sea | (Nguyen et al., 2016) |
| | NOx | Transport optimization and oil field development | (Sahebi, Nickel et Ashayeri, 2014); (Azadeh et al., 2017) |
| | $SO_2$ | Transport optimization and oil field development | (Azadeh et al., 2017) |
| | Wastewater | Transport optimization | (Sahebi, Nickel et Ashayeri, 2014); (Al-Sharrah, Lababidi et Ali, 2016); (Azadeh et al., 2017) |
| Refinery | $CO_2$ | Renewable energy | (Dhaheri et Diabat, 2010); |
| | | Fuel switching | (Dhaheri et Diabat, 2010); (Alhajri et al., 2013), (Gezehei et Almehrezi, 2013); (Liu, Kayyali et Yousef, 2013); (Zhao, Rong et Feng, 2014); (Hadidi et al., 2016) |
| | | Carbon capture | (Dhaheri et Diabat, 2010); (Alhajri et al., 2013); (Kangas, Nikolopoulou et Attiya, 2013) |
| | | Load shifting | (Alhajri et al., 2013) |
| | | Optimization tools | (Khor et Elkamel, 2010); (Gezehei et Almehrezi, 2013); (Liu, Kayyali et Yousef, 2013); (Al-Sharrah, Lababidi et Ali, 2016); (Hadidi et al., 2016); (Azadeh et al., 2017a); (Alnifro et al., 2017); (Moradinasab et al., 2018) |
| | $SO_2$ | Fuel balancing | (Ba-Shammakh, 2010) |
| | | Fuel switching | (Ba-Shammakh, 2010); (Gezehei et Almehrezi, 2013); (Zhao, Rong et Feng, 2014); (Hadidi et al., 2016) |
| | | Fuel gas desulfurization | (Ba-Shammakh, 2010) |
| | | Optimization tools | (Khor et Elkamel, 2010); (Gezehei et Almehrezi, 2013): (Hadidi et al., 2016); (Azadeh et al., 2017a) |
| | $H_2$ | Load shifting | (Alhajri et al., 2013) |
| | | Fuel switching | (Alhajri et al., 2013) |
| | | Capture technology | (Alhajri et al., 2013) |
| | | Optimization tools | (Khor et Elkamel, 2010); (Hadidi et al., 2016); (Azadeh et al., 2017) |
| | VOC | Fuel switching | (Hadidi et al., 2016) |
| | | Optimization tools | (Hadidi et al., 2016) |
| Petrochemical | $CO_2$ | Optimization tools | (Guillén-Gosálbez et Grossmann, 2010); (Ruiz-Femenia et al., 2013); (Ruiz-Femenia et al., 2012) |
| | | Carbon capture | (Liu et al., 2011) |
| | Water Waste | Optimization tools | (Guillén-Gosálbez et Grossmann, 2010) |

## 2.5 Benefits, Challenges, and research gaps

### 2.5.1 Benefits

Sustainability implementation in the petroleum industry has seen significant improvement as attempts have been made to analyze the trade-off between different objectives. Environmental impacts in terms of supply chain operations have thus been assessed through different methodologies Guillén-Gosálbez et Grossmann, (2010) behavior for some production and processing activity levels in the petroleum sector, which makes their decisions more precise and realistic (Attia, Ghaithan et Duffuaa, 2019). This journey started with the implementation of eco-efficient technologies to reduce GHG emissions, especially for refineries (Al Dhaheri et Diabat, 2010; Ba-Shammakh, 2010; Gezehei et Almehrezi, 2013b; Hadidi et al., 2016; Kangas, Nikolopoulou et Attiya, 2013; Nguyen et al., (2016). As a result, green technologies allow countries to meet their obligations by trading emissions credits; as well, such use guides them in assessing their performance, especially in planning large projects. Moreover, the proposed methods guide decision-makers and refinery managers in evaluating the effects of various $CO_2$ mitigation options on profit (Guillén-Gosálbez et Grossmann, 2010; Ruiz-Femenia et al., 2012; Sahebi, Nickel et Ashayeri, 2014; Azadeh et al., 2017).

With the stringent environmental regulations that drive the implementation of the sustainability concept in place, adopting a sustainable supply chain management approach contributes to finding solutions to improve economic performance (profitability maximization, cost reduction, market share increase, and competitiveness). Furthermore, it increases the eco-efficiency of crude oil exploration, production, and distribution. From an environmental management perspective, crucial benefits can be observed at different levels by reducing oil spills, pollution, waste, and carbon footprints. Energy efficiency, eco-friendly products, environmental design, green logistics, and cleaner production are other benefits expected after a successful implementation of sustainability measures in the petroleum sector. For most of the cases reviewed, it was shown that both economic and environmental performance could be achieved simultaneously. Finally, the benefit of adding value and maximizing profitability through the integration of strategic and tactical decisions is one of the critical challenges to achieve long-term and sustainable objectives and avoid the infeasibility of the solutions at the operational level.

### 2.5.2 Research gaps

As shown in the previous sections, the literature in the study needs to be beefed up, and different aspects should be covered in future research. First, the inclusion of the social dimension of sustainable development as part of the modeling effort should be studied since no model was found in which the three objectives (economic, environmental, and social) are considered. Therefore, new criteria and performance evaluation metrics for the social performance evaluation of the supply chain are essential for developing and testing their applicability in the petroleum sector Saeed et Kersten, (2020).

From an environmental perspective, most of the papers concentrate on refineries' environmental issues while neglecting the other impacts from crude oil extraction and transportation since the former are the primary source of emissions through the supply chains (Sahebi, Nickel et Ashayeri, 2014). Further, most of the studies focus on $CO_2$ and fail to integrate $CO_2$ and $SO_2$ emissions since $SO_2$ is a significant gas emitted in the petroleum supply chain (Gezehei et Almehrezi, 2013; Ba-Shammakh, 2010).

Uncertainty consideration in planning a sustainable supply chain is commonly used in research and applied to many industrial sectors. Economic and environmental parameters are uncertain in many cases, and mathematical models must handle the uncertainty to generate robust and optimal decisions. Planning and optimizing the petroleum supply chain under risk and uncertainty is well studied in the literature, with a significant focus on economic performance (Fernandes, Barbosa-Póvoa et Relvas, 2011). The consideration in a sustainable supply chain planning modeling process should be seriously examined in the future since the literature in this area is very limited. Optimizing sustainable supply chain planning under uncertainty will maximize the achievement of expected sustainability results after decisions generated by planning models are applied. Oil prices, supply capacity, and demand are some of the parameters that are particularly affected by uncertainty in the petroleum industry (Ruiz-Femenia et al., 2012; Sahebi, Nickel et Ashayeri, 2014; Azadeh et al., 2017). Nevertheless, this optimization could generate more complexity in solving the models mainly due to the inclusion of the environmental and social parameters (emissions factors, technology), which can also be uncertain (Alhajri et al., 2013; Ba-Shammakh, 2010; Kangas, Nikolopoulou et Attiya, 2013; Moretti et al., 2017; Zhao, Rong et Feng, 2014). The use of a multi-objective optimization technique under an uncertainty cloud be applied in this case Azadeh et al., (2017).

Among the most critical issues, the sustainable integration of the upstream, midstream, and downstream sectors is a complex matter that requires careful consideration (Al-Sharrah, Lababidi et Ali, 2016; Azadeh et al., 2017). The refinery sector is the most responsible for emissions. Therefore, our first gap to be filled relates to selecting optimal $CO_2$ reduction strategies to support the refinery decision to get the best mitigation technology at minimum cost and avoid negative effects on profit (Al Dhaheri et Diabat, 2010; Ba-Shammakh, 2010; Gezehei et Almehrezi, 2013b; Kangas, Nikolopoulou et Attiya, 2013; Hadidi et al., 2016; Nguyen et al., 2016).

Moreover, every part of the petroleum refinery needs to be modeled by applying a reduction technology for every air pollutant where possible, in order to get a zero-emissions refinery (Al Dhaheri et Diabat, 2010; Ba-Shammakh, 2010; Kangas, Nikolopoulou et Attiya, 2013; Alnifro et al., 2017). As well, adopting a carbon capture technology brings about significant profitability gains in several scenarios (Kangas, Nikolopoulou et Attiya, 2013; Nguyen et al., 2016). Refinery modeling incorporates a more realistic refining process flow, especially by adopting more nonlinear models for process units (Kangas, Nikolopoulou et Attiya, 2013). Creating an approach of integrating production planning and energy system optimization for refineries and petrochemicals is very important. Regarding environmental performance, life cycle assessment (LCA) principles aimed at directing the focus on direct emission, wastewater, fugitive, storage tank, and transportation (Azadeh et al., 2017; Guillén-Gosálbez et Grossmann, 2010; Ruiz-Femenia et al., 2012; Sahebi, Nickel et Ashayeri, 2014).

In the crude sector, petroleum extraction and production in producer countries are becoming more complex as they must tackle political issues and meet specific technological and regulatory requirements (Moretti et al., 2017; Sahebi, Nickel et Ashayeri, 2014a; Azadeh et al., 2017). There should be a greater focus on oil field development instead of more exploration. (Sahebi, Nickel et Ashayeri, 2014 ; Azadeh et al., 2017). More studies should be done to provide real data about costs and specifications regarding crude oil availability at a given market price because it is an essential factor that affects profits (Kangas, Nikolopoulou et Attiya, 2013; Gezehei et Almehrezi, 2013). Finally, benefits and opportunities should be developed by improving communications by both the government and the private sector (Kangas, Nikolopoulou et Attiya, 2013; Moradinasab et al., 2018).

## 2.6 Conclusions

This paper presents a systematic research literature review to identify published review papers covering the mathematical programming models for sustainable supply chain planning in the petroleum industry. The descriptive analysis carried out provides a summary overview of the twenty-three (23) selected papers. The papers were published to describe and provide different decision-making tools and models to make the petroleum industry more sustainable. Using the results obtained based on the defined classification scheme, we propose a taxonomy framework as a reference to help the supply chain planner in their modeling efforts toward sustainable decision-making. Unfortunately, in the literature, the social dimension is frequently evaluated based on qualitative measures and is still challenging to quantify.

Most of the proposed modeling approaches focus on revenue maximization and neglect cost minimization. Moreover, from an environmental modeling perspective, the mitigation of $CO_2$ dominates the optimization process since the quality of the data available on $CO_2$ emission factors is accurate enough to address an acceptable evaluation of the total supply chain carbon emissions. The implementation of sustainability in different case studies could be useful in assessing sustainability dimensions and supporting decision-makers to get reasonable results.

However, our literature review paper presents some limitations due to the research methodology used. The first limitation is due to the limited number of model-related research papers (mathematical models in the planning of a sustainable supply chain in the petroleum industry) obtained after the material selection step. As a future research direction, we believe that it is crucial to include papers that do not necessarily use mathematical techniques (conceptual model, survey, empirical studies). The second limitation of this study is related to using a specific classification scheme to analyze the reviewed papers and answer the research questions.

# CHAPTER 3

# SUPPLY CHAIN PLANNING IN THE PETROLEUM INDUSTRY: THE LIBYAN PETROLEUM SECTOR CASE STUDY

## 3.1 Introduction

The petroleum industry is at the heart of our modern societies. It is considered a strategic industry worldwide since oil products are the second most consumable resource across next to water (Al-Husain, Assavapokee et Khumawala, 2006). It generates wealth for the industries and countries. The petroleum industry creates a challenge in terms of supply chain development because different products are widely used in other economic activities with different costs. Furthermore, the consumption of petroleum products, especially in transportation, will be increasing in the future (BP., 2013). On the one hand, petroleum is the most important sector for the gross domestic product (GDP) and export incomes. On the other hand, it created many challenges for both academics and practitioners. Therefore, the optimization of supply chain operations is critical to managing the petroleum supply chain successfully. Traditionally, the petroleum supply chain comprises three streams: upstream, midstream, and downstream.

The petroleum supply chain starts with crude oil production provided to the refineries and petrochemical and then supplied all over the world (Al-Husain, Assavapokee et Khumawala, 2006). In the past, supply chain planning models are developed and tested in real cases from a purely economic perspective and proposed different solutions on how to reduce costs and maximize profit. Optimization of the petroleum organization profit is considered as one of the biggest challenges SCM. Further, SCM can generate a huge profit by providing the best design of the petroleum supply chain network. It is also important to notice that the petroleum sector suffers from a lack of management between parties and miscommunication among the sectors (upstream, midstream, and downstream), stockholders, and suppliers (Al-Othman et al., 2008). Therefore, in this section, we will discuss the recent developments in supply chain planning and modeling in the petroleum sector and discuss the techniques and methods used to achieve more efficiency. Also, we focus on research studies with a broad perspective that looks to the integration of the different streams simultaneously.

## 3.2 Literature review

The petroleum supply chain management area has become an interest for many researchers and practitioners, especially in economic analysis. The literature has been targeting separately crude, refinery, and petrochemical supply chain using various methodologies Sahebi, Nickel et Ashayeri. (2014) developed a mathematical model for profit maximization by considering long-term strategic decisions (Sahebi, Nickel et Ashayeri, 2014). The actual case study results from the Persian Gulf show that the technology selection for crude extraction affects the profit for a long-term horizon. In another study, some authors proposed a mathematical formulation and an optimization model for the production planning at the processing refinery units (Zhao, Rong et Feng, 2014). They showed that the integration between the production and utility systems refine the optimal unit operations and improve overall profit. Hadidi et al. (2016) formulated an optimization model to identify the best technologies for pollution mitigation in petroleum refineries at the minimum cost. Using a case study in Saudi Arabia refineries, gas emissions (Nitrogen oxides: NOx, Sulfur oxides: Sox, and volatile organic compounds: VOC) reduction was achieved and vary between (20% and 90%). Al-Sharrah, Lababidi et al. i. (2016) proposed and tested a linear programming model to optimize an entire petroleum organization (crude production, refineries, petrochemicals, and downstream). They used the model to measure the impact of the optimal production scenarios and how to improve economic performance.

Furthermore, Azadeh et al. (2017) presented an optimization planning model to study how the integration of upstream and midstream streams contributes to profit maximization. The results show that reducing production costs and increasing production capacity have the same effects on profit. They are using a different case study, Ghaithan, Attia et Duffuaa. (2017) develop a multi-objective optimization model to minimize the total cost, maximize the total revenue, and maximize the service level. Lima, Relvas et Barbosa-Povoa. (2018) discussed the tactical planning of the downstream oil supply chain distribution problem of refined products and analyzed petroleum price and demand uncertainties. Moradinasab et al. (2018) develop a mixed-integer linear program model for the downstream oil supply chain and a game theory approach under three objective functions: minimize pollution, maximize profit, and maximize job creation. More recently, Attia, Ghaithan et Duffuaa. (2019) proposed a multi-objective tactical planning model to optimize the upstream oil and gas simultaneously. The model considers three objectives: environmental impact, depletion of natural resources, and minimizing cost, and maximizing revenue. The results showcase how the proposed model can support the decision-maker to make a tradeoff analysis of different production plans subject to sustainability constraints. Finally, Al-Othman et al. (2008) developed a petroleum supply network model. They addressed the integration of all levels upstream, midstream, and downstream.

In summary, the literature review indicates that these models focus on separate streams in the petroleum sector and can't support the optimization of strategic planning from the country level. An integrated model that includes the different streams (upstream, midstream, and downstream) will help the decision-maker plan the use of the other reserves of oil (wells) strategically. Also, to optimize the production plans for refineries and petrochemical plants at the country level to maximize the revenue from the whole petroleum industry sector. Therefore, in this work, we propose a novel and integrated planning model to optimize the petroleum supply chain at the country level. The main contribution of this work is that it is the first study that includes the different streams together (crude, refinery, petrochemical, and transportation) in the same model.

This developed model is applied for the first time to a real case study in Libya to analyze the petroleum sector from a supply chain perspective. Also, to show the improved model application, visualize and validate the results from the optimization model. We introduce a multi-period and multiproduct model, including several decisions (production, transportation, and distribution). A scenario-based analysis is conducted to evaluate the impact of uncertainty and risk events on supply chain performance. The main objective is to identify the possible improvement of supply chain performance in petroleum at the country level.

The remainder of this chapter is organized as follows. Section 2 presents the motivation and problem description. A simplified mathematical model and the data collected are introduced in section 3. Comprehensive analysis and some managerial insights are shown in section 4. Finally, a conclusion that discusses the main results and future research directions are presented in section 5.

### 3.3 Motivation and problem description

Petroleum-producing countries, such as Libya, which is ranked in the top 20 in 2018 with approximately 1,039 thousand barrels per day (bbl/d) (U.S Energy Information Administration, 2019), need to revise their supply chain strategy for production, refining, petrochemical, and transportation. Strategy development is so complex because several parameters have an impact on the decision-making process. It needs a long-term planning process and must consider the demand and price of different products and the capacity of the supply chain network.

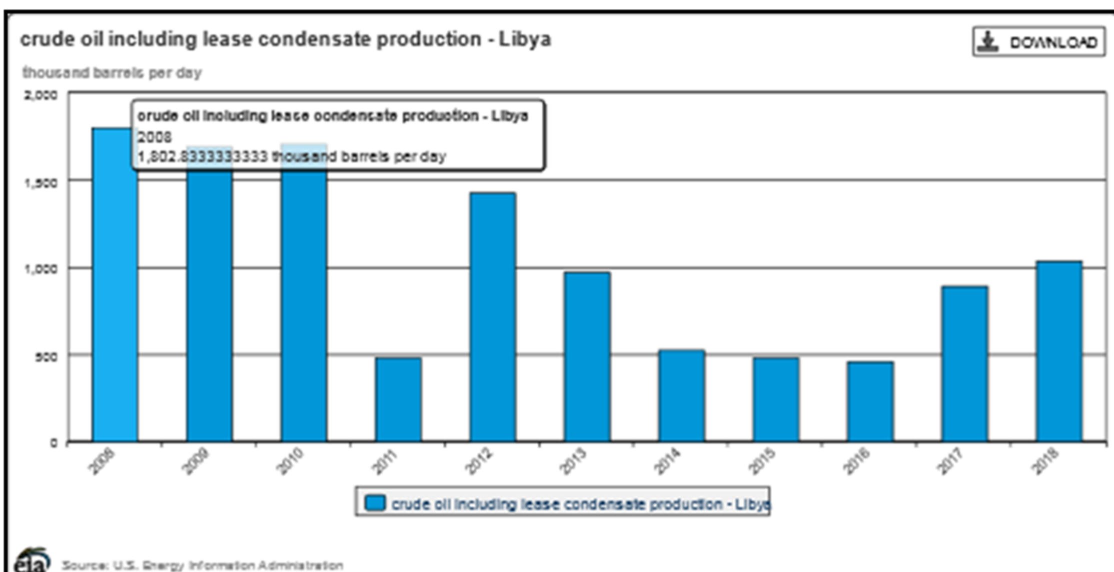



Figure 3.1 Libyan crude oil production

Moreover, for each stream in the petroleum supply chain, we have a possibility of instability in the international market for the demand and price and possible production uncertainty related to the risk due to political issues. As a result, the profitability and network capacity are not guaranteed and might lead to revenue losses. For instance, the Libyan production was high in 2010, with 1,802 thousand barrels per day. However, due to political issues and instability, the production is reduced to almost 42% reduction is observed as shown in Fig 3.1.

Since demand is decreased and the cost of facilities operations is high, it is important to design the optimal network to adjust the production efficiently. So, the question here is how to help the decision-maker in establishing the best use of all the production facilities in the network to deliver the demand and respect the OPEC quota.

### 3.3.1 Problem description

In this paper, in order to build a model adapted to the reality of the petroleum supply chain, we consider an extended supply chain network to tackle the problem from a country-level perspective. In this section, the flowchart is shown in Figure. 3. illustrates the processing stages of the proposed model for the Libyan petroleum sector supply chains at different levels. The petroleum organization extracts the crude from several potential onshore and offshore wells. Four grades of crude are produced (very Light, light, medium, and heavy) with different API numbers (American Petroleum Institute). The extracted crude is moved by using different transportation modes, mostly through pipelines to the local refineries. Other types of crude oil are exported to the international markets (European Union, Asia, and North America) through export terminals.

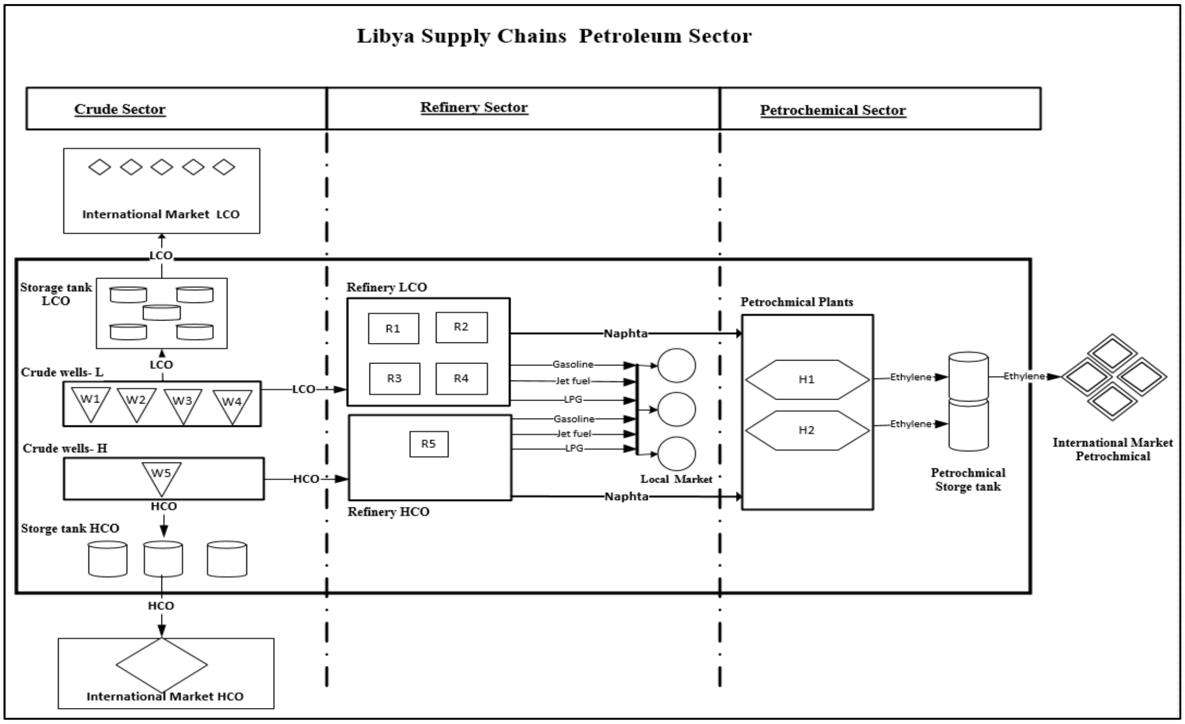



Figure 3.2 processing stages for the petroleum sector

The main task is to transform the crude to value products at the refinery level by various transformation technologies with processing units. The main products considered in this study are naphtha, kerosene, gas oil, asphalt, jet, diesel fuels, and lubricants. In addition, the refinery products might be exported to market sources, used locally, or fed to local petrochemicals. The petrochemical plants produce high-value products like ethylene, propylene, styrene, butadiene, and benzene. Finally, we consider that the planning horizon for the coming 20 years and is divided into different periods of one year. Several essential decisions must be made in this supply chain, including extracting quantity, the flow of oil from wells to the refinery, and product shipment from the plant to the demand.

### 3.3.2 Model development

This section presents a deterministic mathematical model for optimizing the petroleum supply chain sector, including the sets, parameters, and continuous decision variables. Also, the proposed model includes all entities and their connections from oil wells to petrochemical plants.

- **Model assumption**

In this section, we show how the real problem is translated into the proposed model. We propose a generic optimization model for sector petroleum supply chains at different levels (crud wells, refinery, petrochemical, and transportation links). First, the petroleum organization has extracted the crude from the number of potential onshore or offshore platforms $w \in W$. Three grades of crude petroleum are produced (light, medium, and heavy) $p \in P$. The extracted crude petroleum is transferred by using transportation mode $v \in V$ mostly through pipelines to the refineries. The other crude petroleum is exported to the international markets $j \in J$ by exportation terminals.

We aggregate the wells based on geographic location to avoid the variation of the production cost. Also, we assume that using the same technology with the same depth reduces the complicity of the model. Second, at the refinery level $r \in R$, the main task is to transform the crude petroleum to value refined products $e \in E$, such as naphtha, kerosene, gas oil, asphalt, jet, diesel fuels, and lubricants. The refinery products are used locally or fed to petrochemical plants. The petrochemical plant $h \in H$ receives a specific feedstock (Naphtha and gas) from the petroleum refinery. Third, the petrochemicals plants produce high-value products $n \in N$ like ethylene, propylene, styrene, butadiene, and benzene. Finally, we consider that the planning horizon years and it is divided into different periods in the year $t \in T$.

- **Mathematical formulation**

The supply chain optimization model is developed by Al-Othman et al. (2008). This model is a deterministic planning model with a multi-period that considers all levels of the supply chain of a petroleum organization. Also, it consists of all activities related to crude oil production, processing, and distribution, including different costs and different constraints. The list of sets, parameters, and continuous variables is presented.

**Sets**

W: Set of crude oil wells $w \in \{1,2,...,W\}$

P : Set of Crude oil products $p \in \{1,2,...,P\}$

J: Set of Crude oil markets $j \in \{1,2,...J\}$

I: Set of Storage tanks for Crude oil $i \in \{1,2,...I\}$

R : Set of Refineries $r \in \{1,2,...,R\}$

E: Set of Refinery products $e \in \{1,2,...,E\}$

S: Set of Refinery markets $s \in \{1,2,...,S\}$

H: Set of Petrochemicals plants $h \in \{1,2,...,H\}$

Z: Set of Petrochemicals markets $z \in \{1,2,...,Z\}$

N: Set of Petrochemicals products $n \in \{1,2,...,N\}$

K: Storage tank for petrochemical products $k \in \{1,2,...,K\}$

V: Set of transportation modes $v \in \{1,2,...,V\}$

T: Set of time periods $t \in \{1,2,...,T\}$

**Crude oil-related parameters**

$LC_{w}^{C}$= Setup cost of location well $w \in W$ \$

$PRC_{wpjt}^{C}$ = Unit transportation cost of crude oil product $p \in P$ transported from well $w \in W$ to the crude market $j \in J$ t $t \in T$,(\$/bbl)

$PRR_{wprt}^{C}$ = Unit transportation cost of crude oil product $p \in P$ transported from well $w \in W$ to the refinery $r \in R$ at $t \in T$ (\$/bbl)

$FCC_{pjt}^{C}$ = Unit selling price of crude oil $p \in P$ to market $j \in J$ at period $t \in T$ (\$/bbl)

$EXC^{C}_{pwgt}$ = Variable extraction cost of crude oil product $p \in P$ at wells $w \in W$ at $t \in T$ (\$/bbl)

$DC^{C}_{pjt}$ = Demand of crude oil product $p \in P$ by crude market $j \in J$ at period $t \in T$ (bbl/y)

$SC^{max}_{p}$ = Overall storage capacity for crude oil product $p \in P$ (bbl/y)

$VC^{max,min}_{t}$ = Max and Min production level of crude oil production at the period $t \in T$ (bbl/y)

$\gamma^{C}_{pj}$ =Yield of crude oil product $p \in P$ produce at well $w \in W$ from the market $j \in J$ (bbl)

**Crude oil-related continues decisions Variables**

$XC^{C}_{pwjt}$ = flow of crude product $p \in P$ transported from well $w \in W$ to market $j \in J$ during period $t \in T$ (bbl/y)

$XR^{C}_{pwrt}$ = flow of product $p \in P$ transported from well $w \in W$ to refinery $r \in R$ at $t \in T$ ,(bbl/y)

$VC^{C}_{pwgt}$ = Extracted Quantity of crude product $p \in P$ at well $w \in W$ during period $t \in T$ (bbl/y)

$SC^{C}_{pit}$ = Quantity of crude $p \in P$ kept in the storage tank $i \in I$ of crude at period $t \in T$ (bbl/y)

**Crude oil related Binary decision variables**

$BW^{C}_{wt}$ = Binary variable takes a value of 1 if we locate well $w \in W$ at period $t \in T$ , 0 otherwise

**Refinery related parameters**

$CSR^{R}_{er}$ = Storage cost of product $e \in E$ at refinery $r \in R$ ,(\$/bbl)

$CVR^{R}_{er}$ = Production cost of refinery product $e \in E$ from refinery $r \in R$ , (\$/bbl)

$LR^{R}_{r}$ = Setup cost (fixed cost) of refinery location $r \in R$

$SR^{R\max}_{e}$ = Overall storage capacity for a refinery, (bbl/y)

$PRIS^{R}_{rest}$ = Unit transportation cost of refinery product $e \in E$ transported from refinery $r \in R$ to market $s \in S$ at a period $t \in T$ (\$/bbl)

$PRISH^{R}_{reht}$ = Unit transportation cost of refinery product $e \in E$ transported from refinery $r \in R$ to petrochemical plants $h \in H$ at period $t \in T$ ,(\$/bbl)

$VTR^{R}_{ert}$ = Variable transformation cost of product $e \in E$ at the refinery $r \in R$ at $t \in T$ ,(\$/bbl)

$CCR^{R}_{pr}$ = unit cost of processing crude product $p \in P$ ion refinery $r \in R$ (\$/bbl)

$DR^{R}_{est}$ =Demand of refinery product $e \in E$ by the market $s \in S$ at period $t \in T$ ,(bbl/y)

$FCR^{\max}_{rt}, FCR^{\min}_{rt}$ = Max and min production of crude mix to refinery $r \in R$ at $t \in T$ (bbl/y)

$\varphi_{p,r}$ =Fraction of product $e \in E$ contributing to crude blend of refinery $r \in R$ where $\sum \varphi_{i,r}$ =1

**Refinery related continues decisions**

$XR^{R}_{resvt}$ = flow of refinery product $e \in E$ transported from refinery $r \in R$ to refinery market $s \in S$ by transportation mode $v \in V$ $t \in T$ (bbl/y)

$XHR^{R}_{rehvt}$ = flow of refinery product $e \in E$ transported from refinery $r \in R$ to petrochemical plants $h \in H$ by transportation mode $v \in V$ during the period $t \in T$ (bbl/y)

$SQR^{R}_{ret}$ = Quantity of product $e \in E$ kept in the storage tank at period $t \in T$ (bbl/y)

$VR^{R}_{ert}$ = Production quantity of product $e \in E$ at the refinery $r \in R$ at the period $t \in T$ (bbl/y)

$VH^{R}_{ert}$ = Quantity of refinery product $e \in E$ produced by refinery $r \in R$ and used as a feedstock to the petrochemical plants at the planning period t (bbl/y)

$VCCR^{C}_{prt}$ = Quantity of crude product $p \in P$ processed by refinery $r \in R$ at period $t \in T$ (bbl/y)

**Refinery related binary decision variables**

$BR^{R}_{rt}$ = Binary variable takes a value of 1 if we decide to locate refinery $r \in R$ at period $t \in T$, 0 otherwise

$\lambda_{er}$= Binary variable takes a value of 1 if product $e \in E$ by refinery $r \in R$ use as a feedstock to petrochemical plants, 0 otherwise

**Petrochemical related Petrochemical parameters**

$LH_h^H$ = Setup cost of petrochemical plant Location $h \in H$

$CSH_{nh}^H$ = Storage cost of Petrochemical products $n \in N$ at petrochemical plants $h \in H$ ($/bbl)

$DH_{nzt}^H$ =Demand of the petrochemical product $n \in N$ by market $z \in Z$ at $t \in T$ (bbl/y)

$FHH_{nzt}^H$ = Unit selling price of petrochemical product $n \in N$ to market $z \in Z$ at $t \in T$ ($/bbl)

$SH^{\max}$ = Overall storage capacity for petrochemical plants, (bbl/y)

$VH_{\mathrm{nh}t}^{\max}, VH_{\mathrm{nh}t}^{\min}$ = Maximum & Minimum production level of petrochemical product $n \in N$ at petrochemical plants $h \in H$ at $t \in T$ (bbl)

$TRA_{nvt}^H$ = Unit transportation cost of petrochemical product $n \in N$ transported from petrochemical plants $h \in H$ to petrochemical Market $z \in Z$ at period $t \in T$ ($/bbl)

$VTH_{nhqt}^H$ = Variable transformation cost of one bbl of product $n \in N$ in petrochemical plant $h \in H$ at $t \in T$ ($/bbl)

**Petrochemical related continues decisions variables**

$XH_{n\mathrm{hz}v\mathrm{t}}^H$ = Flow of Petrochemical product $n \in N$ transported from petrochemical plants $h \in H$ to petrochemical market $z \in Z$ by transportation mode $v \in V$ during period $t \in T$ (bbl/y)

$SQH_{\mathrm{hnt}}^H$ = Quantity of petrochemical product $n \in N$s kept in stock at the petrochemical plants $h \in H$ time period $t \in T$ (bbl/y)

$VH_{\mathrm{hn}t}^H$ = Production quantity of petrochemical product $n \in N$ at petrochemical plants $h \in H$ during period $t \in T$ (bbl/y)

**Petrochemical related Binary decision variables**

$BH_{ht}^{H}$ = Binary variable takes a value of 1 if we decide to locate the petrochemical plant $h \in H$ at period $t \in T$ ,0 otherwise.

**Objective functions**

The objective function for the deterministic model is defined to maximize the profit, which is equal to the total revenue minus the total costs, including (production, transportation, and storage cost) $/ bbl. It is expressed by this equation.

$$\text{Max } Z = (Z^{C} + Z^{R} + Z^{H}) \tag{3.1}$$

Where $Z^{C}, Z^{R}, Z^{H}$ are the profitability related to crude oil, refining, and petrochemical sectors, respectively.

**Crude objective function**

Where $Z^{C}$ correspond to the profitability related to the refining sector.

$$Z^{C} = \text{Revenue - Cost} \tag{3.2}$$

Revenue = Flow between well and market * Selling price of crude product =

$$\sum_{w}\sum_{p}\sum_{j}\sum_{t}(XC_{p\mathrm{wj}t}^{C} * FCC_{pjt}^{C}) - (\sum_{w}\sum_{t}(LC^{C}{}_{w} * BW^{C}{}_{wt}) + \sum_{w}\sum_{r}\sum_{v}\sum_{t}(BTCR_{\mathrm{wrv}t}^{C} * COCR_{\mathrm{wrv}t}^{C}) + \sum_{w}\sum_{j}\sum_{v}\sum_{t}(BTC_{\mathrm{w}j\mathrm{v}t}^{C} * COC_{\mathrm{w}j\mathrm{v}t}^{C}) + \sum_{w}\sum_{p}\sum_{t}(EXC_{\mathrm{pwt}}^{C} * VC_{wpt}^{C}) + \sum_{w}\sum_{p}\sum_{t}(CSC_{pw}^{C} * SC_{wpt}^{C})) \tag{3.3}$$

**Refinery objective function:**

Where $Z^{R}$ correspond to the profitability related to refining sector.

$$Z^R = \sum_t \sum_r \sum_v \sum_s (XR^R_{erst} * FRR^R_{est}) - (\sum_r \sum_t (LR^R_r * BR^R_{rt}) + \sum_r \sum_h \sum_v \sum_t (BTRH^R_{rhvt} * COHR^R_{rhvt}) + \sum_r \sum_s \sum_v \sum_t (BTR^R_{rsvt} * COR^R_{rsvt}) + \sum_r \sum_e \sum_t (TRAF^R_{ret} * VR^R_{ert})) \tag{3.4}$$

**Petrochemical objective function:**

Where $Z^H$ correspond to the profitability related to petrochemical sectors

$$Z^H = \sum_h \sum_n \sum_z \sum_t (XH^H_{hnzt} * FHH^H_{nzt}) - (\sum_h \sum_t (LH^H_h * BH^H_{ht}) + \sum_h \sum_z \sum_v \sum_t (BTH^H_{hzvt} * COH^H_{hzvt}) + \sum_h \sum_t (VH^H_{ht} * VTH^H_{ht}) + \sum_n \sum_h \sum_t (CSH^H_{nh} * SH^H_{hnt})) \tag{3.6}$$

**Crude oil Parameters**

$LC^C_w$= Setup cost (Fixed cost) of location well $w \in W$ $

$PRC^C_{wpjt}$ = unit transportation cost of crude oil product $p \in P$ transported from well $w \in W$ to crude market $j \in J$ at period $t \in T$ , ($/bbl)

$PRR^C_{wprt}$ = unit transportation cost of product $p \in P$ transported from well $w \in W$ to the refinery $r \in R$ at period $t \in T$ , ($/bbl)

$FCC^C_{pjt}$ = Unit selling price of crude oil $p \in P$ to market $j \in J$ at period $t \in T$ ($/bbl)

$EXC^C_{pwgt}$ = Variable extraction cost of product $p \in P$ at wells $w \in W$ during period $t \in T$ ($/bbl)

$DC^C_{pjt}$ = Demand of crude oil product $p \in P$ by crude market $j \in J$ at period $t \in T$ (bbl/y)

$SC^{max}_p$ = Overall storage capacity for crude oil product $p \in P$ (bbl/y)

$VC_t^{\max,\min}$ = Max and Min production level of crude oil production at period $t \in T$ (bbl/y)

$\varphi_{\mathrm{p,r}}$ =Fraction of product $p \in P$ contributing to crude blend of refinery $r \in R$ where $\sum \varphi_{\mathrm{p},r}$ =1

$\gamma_{\mathrm{pj}}^{C}$ =Yield of crude oil product $p \in P$ produce at well $w \in W$ from market $j \in J$ (bbl)

**Continues Decisions Variables**

$XC_{p\mathrm{wj}t}^{C}$ = Flow of product $p \in P$ transported from well $w \in W$ to market $j \in J$ at $t \in T$ (bbl/y)

$XR_{p\mathrm{wr}t}^{C}$ = Flow of product $p \in P$ transported from $w \in W$ to refinery $r \in R$ during $t \in T$ ,(bbl/y)

$VC_{pwgt}^{C}$ = Extracted quantity of crude oil product $p \in P$ at well $w \in W$ during $t \in T$ (bbl/y)

$SC_{\mathrm{p}it}^{C}$ = Quantity of crude oil $p \in P$ kept in the storage tank $i \in I$ of crude oil at $t \in T$ (bbl/y)

**Binary Decision variables**

$BW_{\mathrm{w}t}^{C}$ = Binary variable takes a value of 1 if we locate well $w \in W$ at period $t \in T$ , 0 otherwise

**Refinery Parameters**

$CSR_{er}^{R}$ = Storage cost of product $e \in E$ at refinery $r \in R$ ,($/bbl)

$CVR_{er}^{R}$ = Production cost of refinery product $e \in E$ from refinery $r \in R$ , ($/bbl)

$LR_{\mathrm{r}}^{R}$ = Setup cost (fixed cost) of refinery location $r \in R$

$SR_e^{R,\max}$ = Overall storage capacity for Refinery, (bbl/y)

$PRIS_{rest}^{R}$ = Unit transportation cost of refinery product $e \in E$ transported from refinery $r \in R$ to market $s \in S$ at period $t \in T$ ,($/bbl)

$PRISH_{reht}^{R}$ = Unit transportation cost of refinery product $e \in E$ transported from refinery $r \in R$ to petrochemical plants $h \in H$ at period $t \in T$ ,($/bbl)

$VTR_{ert}^{R}$ = Variable transformation cost of $e \in E$ at refinery $r \in R$ at period $t \in T$ ,($/bbl)

$CCR_{p\mathrm{r}}^{R}$ = Unit cost of processing crude product $p \in P$ in refinery $r \in R$ , ($/bbl)

$DR^{R}_{est}$ = Demand of refinery product $e \in E$ by market $s \in S$ at period $t \in T$ ,(bbl/y).

$FCR^{max}_{rt}, FCR^{min}_{rt}$ = Max and min production of crude mix to refinery $r \in R$ at $t \in T$ (bbl/y)

$\varphi_{p,r}$ =Fraction of product $e \in E$ contributing to crude blend of refinery $r \in R$ where $\sum \varphi_{i,r}$ =1

**Continues Decisions variables**

$XR^{R}_{resvt}$ = Flow of refinery product $e \in E$ transported from refinery $r \in R$ to refinery market $s \in S$ by transportation mode $v \in V$ during the period $t \in T$ (bbl/y)

$XHR^{R}_{rehvt}$ = Flow of refinery product $e \in E$ transported from refinery $r \in R$ to petrochemical plants $h \in H$ by transportation mode $v \in V$ during the period $t \in T$ (bbl/y)

$SQR^{R}_{ret}$ = Quantity of product $e \in E$ kept in the storage tank at period $t \in T$ t (bbl/y)

$VR^{R}_{ert}$ = Production quantity of product $e \in E$ at the refinery $r \in R$ at the period $t \in T$ (bbl/y)

**Binary Decision variables**

$BR^{R}_{rt}$ = Binary variable takes 1 if we decide to locate refinery $r \in R$ at period $t \in T$ , 0 otherwise

$\lambda_{er}$ = Binary variable takes 1 if product $e \in E$ by refinery $r \in R$ use as a feedstock to petrochemical plants, 0 otherwise

**Petrochemical Sector**

$LH^{H}_{h}$ = Setup cost of petrochemical plant Location $h \in H$

$CSH^{H}_{nh}$ = Storage cost of petrochemical product $n \in N$ at petrochemical plants $h \in H$ (\$/bbl)

$DH^{H}_{nzt}$ = =Demand of petrochemical product $n \in N$ by market $z \in Z$ at period $t \in T$ (bbl/y)

$FHH^{H}_{nzt}$ = Unit price of petrochemical product $n \in N$ to market $z \in Z$ at period $t \in T$ (\$/bbl)

$SH^{max}$ = Overall storage capacity for petrochemical plants, (bbl/y)

$VH_{\text{nh}t}^{\max}, VH_{\text{nh}t}^{\min}$ = Maximum & Minimum production level of petrochemical product $n \in N$ at petrochemical plants $h \in H$ at period $t \in T$ (bbl)

$TRA_{nvt}^{H}$ = Unit transportation cost of petrochemical product $n \in N$ transported from petrochemical $h \in H$ to market $z \in Z$ at period $t \in T$ ($/bbl)

$VTH_{\text{nh}qt}^{H}$ = Variable transformation cost of $n \in N$ in petrochemical $h \in H$ at $t \in T$ ($/bbl)

**Continues Decisions variables**

$XH_{n\text{hzvt}}^{H}$ = Flow of petrochemical product $n \in N$ transported from petrochemical plants $h \in H$ to petrochemical market $z \in Z$ by transportation mode $v \in V$ during period $t \in T$ (bbl/y)

$SQH_{\text{hnt}}^{H}$ = Quantity of petrochemical product $n \in N$ kept in stock at $h \in H$ at $t \in T$, (bbl/y)

$VH_{\text{hn}t}^{H}$ = Production quantity of petrochemical product $n \in N$ at $h \in H$ during $t \in T$ (bbl/y)

**Binary Decision variables**

$BH_{\text{ht}}^{H}$ = Binary variable takes a value of 1 if we decide to locate petrochemical plant $h \in H$ at period $t \in T$, 0 otherwise.

**Constraints**

Set of constraints have proposed to determine the feasibility of the model. They are classified as four categories: material balance, demand balance, storage constraints, and production yield., they are presented next.

*Crude demand satisfaction*

$$DC_{pjt}^{C} = \sum_{w} XC_{p\text{w}jt}^{C}, \forall p \in P, \forall j \in J, \forall t \in T \tag{3.7}$$

*Refinery demand satisfaction*

$$DR_{est}^{R} = \sum_{r} XR_{rest}^{R}, \forall e \in E, \forall s \in S, \forall t \in T \tag{3.8}$$

*Petrochemical demand satisfaction*

$$DH_{nzt}^{H} = \sum_{h} XH_{\mathrm{h}nz\mathrm{t}}^{H}, \forall n \in N, \forall z \in Z, \forall t \in T \tag{3.9}$$

*Materials balance for crude oil sector*

$$SC_{wpt}^{C} = SC_{wpt-1}^{C} + \sum_{g} VC_{wpgt}^{C} - \sum_{j} XC_{wpjt}^{C} - \sum_{r} XRC_{wprt}^{C} \forall p \in P, \forall w \in W, \forall T > 1 \tag{3.10}$$

$$SC_{wp1}^{C} = SC_{wp1}^{C} + \sum_{g} VC_{wpg1}^{C} - \sum_{j} XC_{wpj1}^{C} - \sum_{r} XRC_{wpr1}^{C}, \forall p \in P, \forall w \in W \tag{3.11}$$

*Materials balance for refinery sector*

$$SR_{ret}^{R} = SR_{ret-1+}^{R} \sum_{w} XRC_{wprt}^{C} - \sum_{s} XR_{rest}^{R} - \sum_{h} XHR_{reht}^{R}, \forall p \in P, \forall r \in R, \forall T > 1 \tag{3.12}$$

$$SR_{re1}^{R} = SR_{re1+}^{R} \sum_{w} XRC_{wpr1}^{C} - \sum_{s} XR_{res1}^{R} - \sum_{h} XHR_{reh1}^{R}, \forall p \in P, \forall r \in R \tag{3.13}$$

Materials balance for the petrochemical sector

$$SH_{hpt}^{h} = SH_{h\mathrm{p}t-1}^{h} + \sum_{r} XHR_{\mathrm{hpz}t}^{R} - \sum_{z} XH_{\mathrm{hpz}t}^{H}, \forall n \in N, \forall h \in H, \forall T > 1 \tag{3.14}$$

*Crude oil production constraints*

$$VC_{\min}^{C} \le \sum_{w} \sum_{p} \sum_{t} VWC_{wpt}^{C} \le VC_{\max}^{C} \quad , \forall t \in T \tag{3.15}$$

*Production yields quantities of refined products produced from a specific kind of crude oil*

$$VR_{reut}^{R} = \sum_{j} \left( \gamma_{\mathrm{p}j} * VCR_{\mathrm{pr}t}^{R} \right) \quad \forall p \in P, w \in W, \forall t \in T \tag{3.16}$$

*Producing of petrochemical products*

$$VH_{\mathrm{hn}t}^{H} = \sum_{j \in P^{R}} \sum_{i \in I^{R}} \left( \gamma_{ns}^{H} \quad VCH_{\mathrm{nh}t}^{H} \right) \quad \forall n \in N, h \in H, \forall t \in T \tag{3.17}$$

*Refinery throughput*

$$VC_{\mathrm{i}t}^{R,k} / VC_{\mathrm{ref}t}^{R,k} = \varphi_{i}^{R,k} / \varphi_{\mathrm{ref}}^{R,k} \quad \forall i \in P^{C}, i \notin \mathrm{ref}, k \in I^{R}, \forall t \in T \tag{3.18}$$

*Bounds on total yield's crude oil in the refineries*

$$VC_{\min}^{\mathrm{R}} \le \sum_{e} VC_{e,t}^{R} \le VC_{\max}^{R} \quad \forall e \in E, t \in T \tag{3.19}$$

*Petrochemicals production bounds*

$$VH^{H}_{ht} \leq VH^{H}_{ht\max} \; \forall n \in N, h \in H, \forall t \in T \tag{3.20}$$

*Storage crude capacities*

$$\sum_{w}\sum_{p}\sum_{t} SQC^{C}_{wpt} \leq SC^{\max}_{p}, \forall w \in W, p \in P, \forall t \in T \tag{3.21}$$

*Storage refinery capacities*

$$\sum_{r}\sum_{e}\sum_{t} SQR^{R}_{ret} \leq SR^{R,\max}_{e}, \forall r \in R, e \in E, \forall t \in T \tag{3.22}$$

*Storage petrochemical capacities*

$$\sum_{h}\sum_{t} SQH^{H}_{ht} \leq SH^{h\max}, \forall n \in N, h \in H, \forall t \in T \tag{3.23}$$

$$\sum_{r} FIXCOST = (\sum_{r}\sum_{t} \mathrm{FIX}_{i}) * BINVR^{R}_{rut} \tag{3.24}$$

Demand constraints, (3.6), (3.7), and (3.8) constraints show the upper and lower crude oil demand for international markets, refinery for local market demand, and petrochemical products for the international market. Material balance constraints: the sum of incoming flow must be equal to outgoing flow through the network at any different sectors. (4.1), (4.2), and (4.3) Constraints represent the material balance for crude oil refinery and petrochemical, respectively. Capacity constraints (5.0), (5.1), and (5.3) express the upper bound and lower bound for crude oil, refinery, and petrochemical storage capacity.

In addition, there are three binary variables presented in this model. The first binary variables $BW^{C}_{wt}$ which represents the location of the well in period t in the model. This variable takes a value equal to 1 if we decide to locate new wells and 0 if not. The other binary variables refinery $BR^{R}_{rt}$ and petrochemical $BH^{H}_{ht}$. The supply chain optimization model is developed by Al-Othman et al. (2008). This model is a deterministic planning model with a multi-period that considers all levels of the supply chain of a petroleum organization.

### 3.4 Case study description and data collection

In this study, a MILP model is developed to maximize the profit and minimize the total cost of upstream, midstream, and downstream segments of the crude oil supply chain. The Libyan petroleum supply chain network is composed of several Oil wells. The crude oil is extracted from five (5) onshore basins and two (2) offshore platforms. Two types of crude oil are produced (Low Crude Oil (LCO) and Heavy Crude Oil (LCO)) and transported via pipelines to feed the local refineries as well as storage tanks and exported to satisfy the international market as agreed in the OPEC quota. Furthermore, the supply chain contains five (5) refineries located in different regions with a total capacity of 380,000 bbl/day. Some of the refinery products (Gasoline, Naphtha, Jet fuel, and LPG) are used to satisfy the local demand. The remaining quantities are used as a feedstock for two (2) local petrochemical plants to produce Ethylene, Methanol, Ammonia, and Urea. Petrochemical products are used to satisfy the need of local industries and international demand (Barker et McLachlan, 2014). This study considers the following scenario for demand in a million barrels (Mbbl) per year from the different sectors (crude oil, petrochemical products, and refinery products) during the next 20 years' time horizon, as illustrated in Fig. 3.3. The forecast is based on the historical data and the global oil supply-demand (Sieminski, 2014).

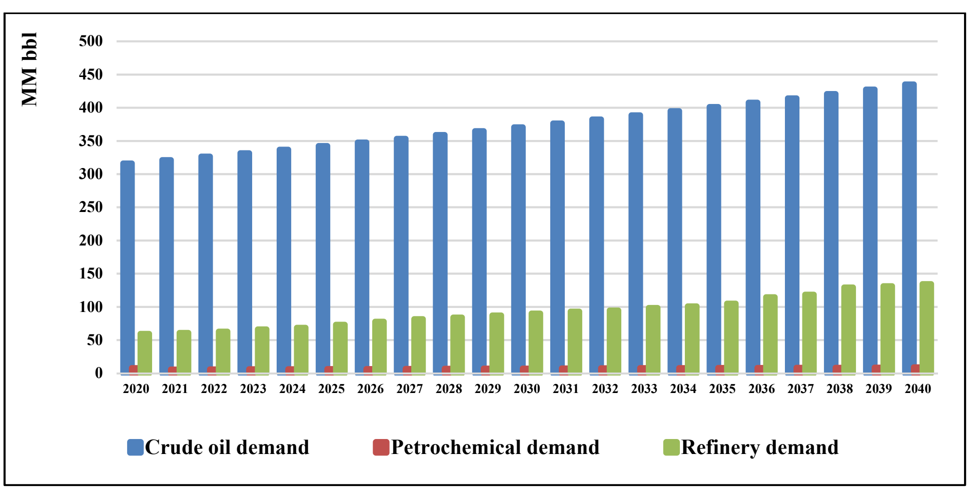
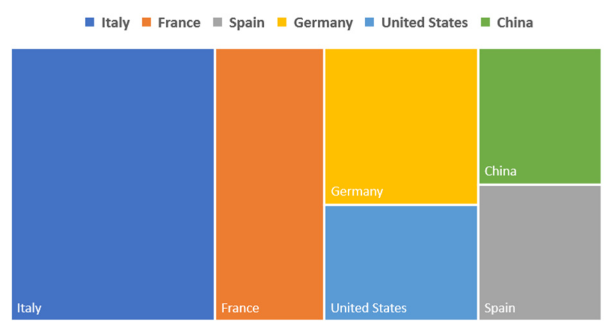



Figure 3.3 Total aggregated demand per sector (Dalheimer et al.,2020)

Regarding market distribution, Fig. 3.3 illustrates the proportion of the local market versus the international market.




a) Crude oil market distribution


b) International versus local market demands

Figure 3.4 Crude oil market distribution international versus local market demands (Dalheimer et al.,2020)

Fig. 3.4 a and b give more details about the international crude oil market distribution by region. Again, the European market is the most important one, followed by the USA and China. Finally, when you look at Fig. 3.5, the European region is the only customer for petrochemical production, where the Netherlands is considered the most important country.

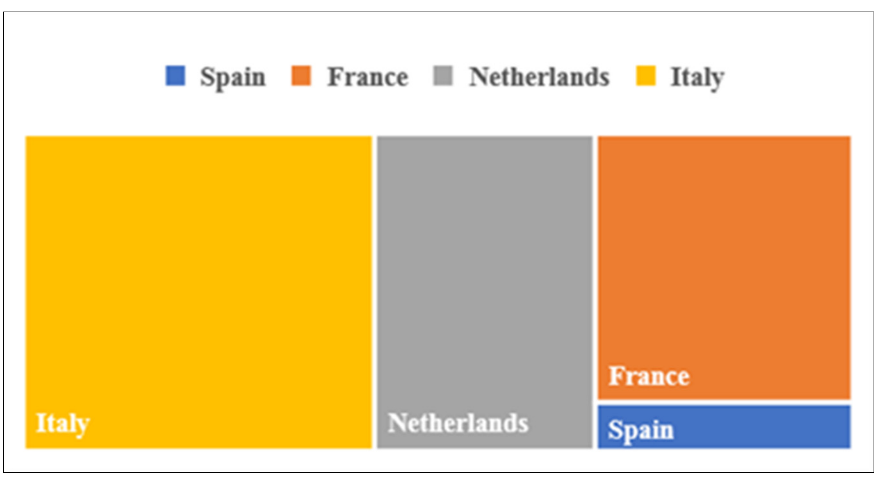



Figure 3.5 Petrochemical market distribution

The next section will present the main results and findings after using the proposed model combined with the collected data.

## 3.5 Results and analysis

Using a commercial software supply chain Guru (SCG), the model is implemented in less than one minute. The obtained model represents 5,340 variables, 400 integers, and 3,695 constraints. The model was validated first using the demand for 2019. After that, we analyze different scenarios. For this study, we will consider three scenarios. For the first one, named the baseline (scenario 1), which represents the optimal supply chain plan that results from using the deterministic model by considering all parameters, the actual rules and constraints described in section 3 are maintained. In the second scenario, we eliminate some rules and constraints to change some policies that have been applied in the previous years, which are not realistic in the future. Finally, in scenario 3, we consider the planning process under some risky events of shutdown the most produced wells. The results for scenario 1 of the aggregated production for the 20 years horizon per product are illustrated in Figure. 3.6.

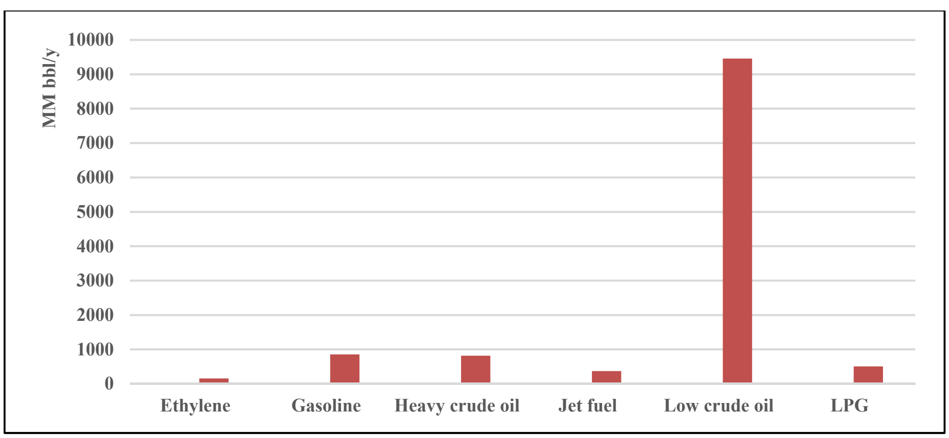



Figure 3.6 Aggregated production quantities per product

Table 3.1 shows the detailed production quantities in Million bbl (MM bbl) and production and transportation costs in Million US dollars (M $) for each product in the different sectors.

The production cost in the crude sector is the most dominating cost. The crude production cost is near 86% of the total cost while refinery 8% and petrochemical 6%. Also, transportation cost has a majority in the crude sector, which has a significant value than others, 84% and 4% in the refinery.

Table 3.1 Production and transportation cost for scenario 1

| Products | Production Cost (M $) | Transportation Cost (M $) | Quantity (MM bbl) | Average cost ($) |
|---|---|---|---|---|
| LCO | 112,605 | 17,506 | 9,457 | 13.76 |
| HCO | 9,783 | 2,038 | 815 | 14.50 |
| Gasoline | 11,104 | 1,708 | 854 | 15 |
| Jet fuel | 1,843 | 737 | 369 | 7 |
| LPG | 2,860 | 1,005 | 502 | 7.69 |
| Ethylene | 9,953 | 386 | 154 | 67 |

Customer flows are illustrated in Figure 3.7, and crude oil shipments satisfy all demands regarding demand satisfaction.

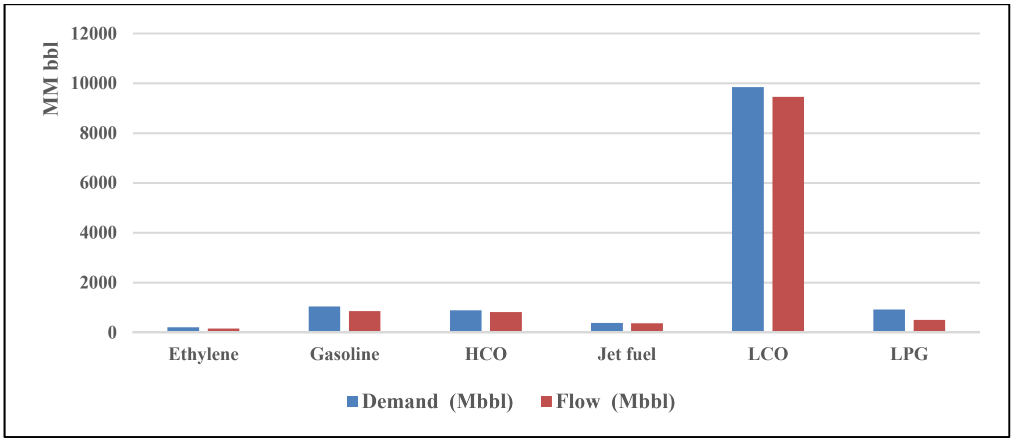



Figure 3.7 Demand VS flow for different products

Tables (3.2) and (3.3) illustrate the profit and service level, which the variation between flow and demand can calculate. We focused on the scenario one baseline to see how the cost is reduced for transportation and production. The wells in the baseline are used, but in scenario two, some wells (W1, W3, and W4) are not used because the production cost is expensive.

Table 3.2 Profit and service level for scenario one

| **Products** | **Demand (MM bbl)** | **Flow (MM bbl)** | **Profit (M $)** | **Service level** |
|---|---|---|---|---|
| LCO | 9,848 | 9,457 | 360,054 | 96% |
| HCO | 886 | 815 | 37,094 | 92% |
| Gasoline | 1,042 | 854 | 81,147 | 82% |
| Jet fuel | 380 | 369 | 26,171 | 97% |
| LPG | 922 | 502 | 41,342 | 55% |
| Ethylene | 205 | 154 | 12,808 | 75% |

The actual capacity and policy rules are not synchronized with future demand. Therefore, it is essential to analyze and implement new rules at the country level to maximize profit and increase the service level. In scenario two, we exclude some of the production constraints included in the baseline scenario to guarantee the minimum production level for each well. In the third scenario, we test the network where we simulate the production interruption in the risky well two (W2). This scenario has decrease service level but increases the profit.

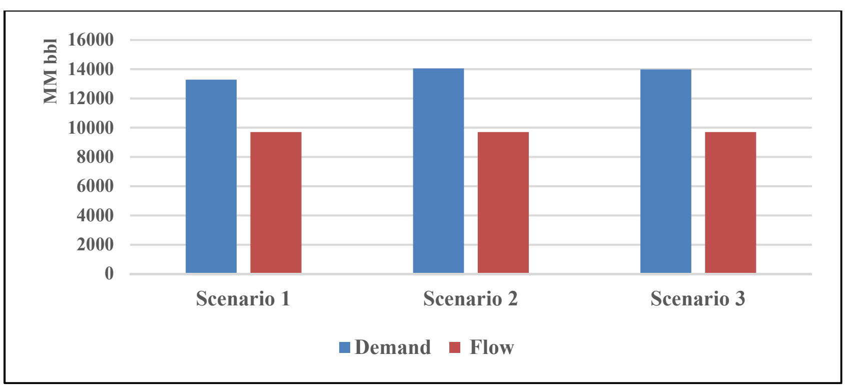



Figure 3.8 Production quantity for the petroleum sector

Table 3.3 Demand, flow profit, and service level in diff scenarios

| Scenarios | Demand (MM bbl) | Flow (MM bbl) | Profit (M $) | Service level |
|---|---|---|---|---|
| Scenario 1 | 13,281 | 9,697 | 558,616 | 73% |
| Scenario 2 | 14,053 | 9,697 | 600,271 | 69% |
| Scenario 3 | 13,980 | 9,697 | 601,198 | 69.3% |

The results are illustrated in Table 3.4 to compare two scenarios (10% increase, 10% decrease in market demand), which shows that the profitability in scenario 1 is more increased by 63% concerning the base case scenario. This represents a case of higher crude oil sales revenues (compared with the base case). However, scenario 2 resulted in a decrease in profitability due to reducing their crude, so crude oil is the high-value product. Surprisingly, the more one transforms, the more one adds value and enhances the asking price oil production level because it is the most products that have more priority to generate high profits. As a result, we need to establish the best strategy for two scenarios (1,2) to face the change of the variation of the production level for each product to still getting the maximum profit.

Table 3.4 Comparison between scenarios 2 and 3

| Scenarios | Products | Profit (M $) | Profit increase/decrease |
|---|---|---|---|
| **Scenario + 10%** | Ethylene | 14,089 | 10% |
| | Gasoline | 89,262 | 10% |
| | HCO | 4,0804 | 10% |
| | Jet fuel | 29,086 | 10% |
| | LCO | 407,320 | 13.13% |
| | LPG | 46,363 | 9.97% |
| | **Total** | **626,924** | **12.23%** |
| **Scenario -10%** | Ethylene | 11,528 | -10% |
| | Gasoline | 73,033 | -10% |
| | HCO | 33,385 | -10% |
| | Jet fuel | 23,798 | -10% |
| | LCO | 256,486 | -13.13% |
| | LPG | 37,961 | -9.97% |
| | **Total** | **492,492** | **-11.84%** |

## 3.6 Conclusions

This paper aims to develop an optimization model for supply chain planning in the petroleum industry, which accounts for economic performance. The developed model considers the decisions related to the flow between nodes, production capacities from the country-level perspective, and how to satisfy the demand to maximize profit from local and international markets. We examined the model's performance through real data of the Libyan case study with a time horizon analyzed and covers 20 years.

From the case-study analysis, we can conclude that the generic mathematical model allows improvements in the economic side as a first step and offers essential managerial insights. Also, it will enable economic performance development depends on the future energy market. Should future work include environmental and social problems as the second step to establish a strategic plan for solving sustainability dimensions.

# CHAPTER 4

# AN OPTIMIZATION BASED STRATEGIC PLANNING MODEL FOR GREENING SUPPLY CHAIN IN PETROLEUM INDUSTRY

## 4.1 Introduction

The petroleum industry is a significant part of the world economy, specifically in the energy sector. Also, this industry plays a substantial role in supplying transportation needs and providing the customers' petroleum products requirements. Nevertheless, the industry's activities (extraction, refining, production, storage, transportation, and distribution) have caused environmental problems and draws attention toward more sustainable petroleum supply chain management in many countries Dudley (2018). Sustainable supply chain management at the country level in the petroleum industry is most complicated and advanced. The reason behind that this sector covers integrated activities from the crude sector to the final customer through refinery and petrochemical sectors. Also, other considerations add uncertainty in environmental regulations and involve changing the system due to the high competition in a globalized market, limit GHG emits, and fluctuating demand and prices Baumeister et Kilian (2016); Hussain, Assavapokee et Khumawala (2006). This pressure comes from different regulations and laws worldwide that push the petroleum sector and its activities to green the supply chain, requiring long-term planning. Mani, Agrawal et Sharma (2015); Y. Lakhal, H'Mida et Islam (2007).

Due to tremendous pressure (Florescu *et al.*, 2019), organizations must optimize their economic, environmental, and social performances when managing their supply chain to respect global regulation and prepare the transition towards sustainable petroleum supply chains (Abdussalam *et al.*, 2021). Due to the continuous development of technologies, higher and more stringent standards are put forward for optimizing these complex supply chains. It has created a new challenge and makes it interesting for academics and practitioners. This increases the need for developing sustainable supply chain planning models that overcome these issues and achieve more integration between segments (Seuring et Müller, 2008). Supply chain optimization models help supply chain managers make the right decisions across stages to generate a considerable profit and reduce environmental impact through an effective and modern supply chain (Chima et Hills, 2007). In this regard, this study's key motivation comes from the solid global desire to reduce environmental impacts such as air, water, and soil pollution. The petroleum industry's supply chain is one of the most dynamic sectors worldwide. It is essential to emphasize risk assessment in managerial petroleum activities for long-term decisions. Further, it is necessary to evaluate with precision the relationship between environmental risk and economic considerations.

Previous studies in this field focus on operational risks in production, inventory, ecological damage, and loss of demand (Al-Sharrah, Lababidi et Ali, 2016; Azadeh *et al.*, (2017); (Guillén-Gosálbez et Grossmann, 2010) ; (Ruiz-Femenia *et al.*, 2013). Based on the literature review carried out in this context, we identified a gap in the petroleum supply chain's strategic planning. To the best of our knowledge, no research study addressed the problem of green supply chain design, including all petroleum sectors, and considering strategic risks relayed to adopting new environmental regulation. These risks might occur at any time, are certainly not possible to be avoided, but they have a significant impact on the supply chain performance. The environmental risk assessment should be included as a part of the strategic planning exercise to identify clear plans that minimize ecological impacts.

The Libyan country is one of the main producers of oil and gas in the world. However, Libyan petroleum companies have widely ignored sustainability and environmental management (Emodi et Boo, 2015). Therefore, this paper considers the Libyan oil sector since the industry faces different challenges, including environmental risk. A mixed-integer linear programming model and a multiobjective formulation are used to address this problem and provide decision-makers with a comprehensive strategic supply chain planning tool to evaluate different green supply options and achieve a sustainable supply chain solution. The specific contributions of this work are as follows. First, we a develop a supply chain planning model to integrate economic and environmental to help decision-makers in the process of greening in the petroleum sector in Libya (government) to show the validity of the proposed approach. Second, the model presents a generic approach to include the supply chain's critical components at the country level (crude, refinery, petrochemical, and transportation) that influence eco-efficiency. Finally, the present study proposes a decision-making framework to evaluate the marginal abatement costs for different environmental scenarios and varying mitigation strategies.

## 4.2 Motivation

This study is motivated by a real problem faced in Libya. Indeed, Libya has 27 giant oil production fields, including 896 wells to produce different crude grades with varying API (American Petroleum Institute) numbers (M. Abdulaziz, 2013). More than 80% of the crude oil is exported to the international markets (European Union, Asia, and North America), as shown in figure 1 through export terminals. The rest is processed by using different transportation modes, mainly through pipelines to local refineries. Several decisions must be made in this supply chain, including how much to extract, the flow of oil from wells to the refinery, and product shipment from the plant to the demand nodes. The Libyan petroleum sector emissions have increased from 52.2 Mt $CO_2$ in 2010 to 57.9 Mt $CO_2$ in 2017 Rahil et al., (2019).

For this matter, Libya is 56th from 225th of the most polluted countries and contributing to 0.22% of global emissions Nassar, Aissa et al, (2017). Therefore, the Libyan government needs to implement emissions reduction strategies to reduce GHG emissions, mainly $CO_2$ Etelawi, Blatner et McCluskey, (2017). Thus, the objective is to help decision-makers establish the “best” supply chain strategy for mitigation $CO_2$ emissions and efficiently use the supply chain network to deliver the demand concerning the OPEC quota. This study aims to create an optimization-based planning model and apply it to a case study involving data from the Libyan petroleum industry. The data has been collected directly from the (NOC) annual reports at different levels (crude oil, refinery petrochemical) from the country's perspective.

The planning model will provide a comprehensive strategy including three scenarios to mitigate environmental risk at the minimum possible cost. The mathematical model's description is explained in the following sub-sections, including problem definition and the methodology used to answer the research questions, model elements, and model formulation.

## 4.3 Problem definition and methodology

Strategy development is complex, and it needs a long-term planning process sensitive to several parameters that impact the decision-making process. The extended petroleum supply chain network considered in this study includes crude oil wells, refineries, petrochemicals, and domestic and foreign demand markets connected with different transportation modes.

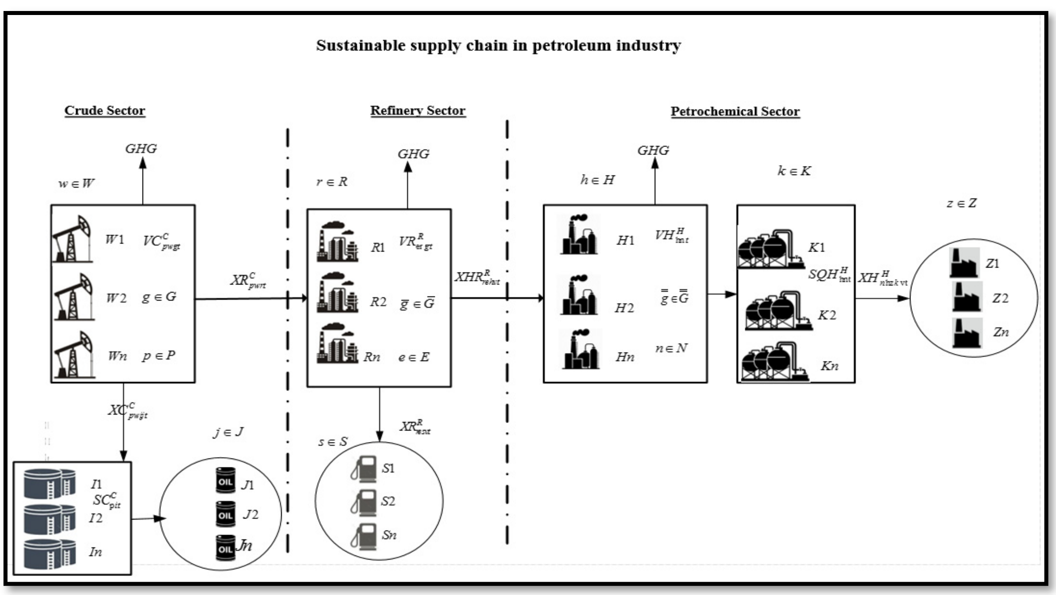



Figure 4.1 The network of the petroleum supply chain sector

The eco-efficient model, in this case, aims to minimize both total costs and $CO_2$ emissions over the planning horizon and provide accurate data to establish the best strategy to decarbonize the supply chain in the petroleum sector under the uncertainty of environmental regulations. Figure 4.1 illustrates the proposed model's processing stages for the petroleum supply chain at different levels.

Several assumptions are stated to establish the mathematical model. The choice of technologies to be used at the different stages of the supply chain plays an essential role in reducing carbon dioxide emitted into the atmosphere Guo et al., (2020). We assume that the technologies are selected for crude extraction based on the oil field characteristics and geographical conditions to increase efficiency and reduce the environment's effects. Second, the downstream must meet the market demands for various products with $CO_2$ emissions reduction targets. For this matter, refineries and petrochemical need to make more effort (investment) to reduce $CO_2$ emissions. Therefore, different technologies can be considered to reduce the $CO_2$ emissions of refining and petrochemical processes. Finally, we assume that new environmental legislation will be introduced to reduce carbon emissions and create a transition toward a more sustainable petroleum sector Knittel, (2012).

Various kinds of risks can occur at any time and certainly not possible to be avoided. This study considers the uncertainty related to the choice of pollution control mechanism that can be influenced by economic risks, including oil price collapse, loss of demand, high operating costs, disasters, and shortages in some geographical locations. These can significantly affect exploration, development, and production.

A system thinking-based-methodology approach is adopted to solve this problem because it looks at the overall network rather than specific system parts. Moreover, it tackles complex issues and risk factors to highlight the change in the organization's performance. Also, it helps practitioners to bring together many different parameters to identify problems and solutions to challenges. Therefore, we propose a four-step methodology that follows the system thinking approach Grösser, (2017). The first step investigates the literature review from a modeling perspective to identify the research gaps, opportunities, modeling issues, system definition, and delimitations. In the second step, we develop a mathematical model to evaluate the performance from an economic perspective.

The optimization model aims to help the decision-makers identify investment decisions at each sector, the production flow decisions between nodes, production capacities at each level, and how to satisfy the demand to local and international markets. In the third step, we integrate the environmental dimension after gathering the baseline model's data. The goal is to study the effects of environmental regulation and estimate the cost change after implementing mitigation strategies for each petroleum sector. Using a case study that covers the Libyan petroleum sector, investments in different projects and technologies are evaluated and analyzed to move toward more sustainable and greener petroleum supply chains. Finally, in step 4, we provide some sensitivity analysis to study the impact of uncertain parameters such as demand and emission factors on planning decisions and model solutions.

## 4.4 Model elements

Based on the previous section's problem, a model for strategic supply chain planning is proposed. First, the definition of performance indicators for strategic supply chain planning in the petroleum industry is necessary. It provides feedback on continuous improvement towards this industry's goals. This study defines the total supply chain cost as an objective to minimize (Attia, Ghaithan et Duffuaa, 2019); (Moradinasab *et al.*, 2018). From the literature review, we observed that $CO_2$ emissions are mostly used to evaluate the supply chain's environmental performance Hadidi et al., (2016). Therefore, we include direct emissions from the following activities: extraction, production, refining, petrochemical, and transportation. For the crude sector, exploration and production sites, either onshore or offshore, using technology $g \in G$ will release $CO_2$ emissions ( $E^c$ ) during their operation. Also, transportation and distribution activities that generate emissions $E^V$ include pipeline trucks and maritime. At the refinery level $r \in R$, a refinery's main task is to transform crude to value refined products $e \in E$ by various transformation technologies $x \in X$. If we implement one technology, we should consider different costs (fixed cost, operation cost, variable cost). Petrochemical products result from complex transformation technology $q \in Q$ with different processes, such as reaction, distillation, and absorption. Finally, the amount of $CO_2$ generated by transportation modes is equal to the total flows of all sector products times the emission factor of different transportation modes. Since our study focuses on the country level and is looking to integrate strategic and tactical decisions, we consider the planning horizon for 20 years. It is divided into different periods in one year $t \in T$ to solve this problem and see the impact of technology change on the future and how to transform the whole sector towards a greener petroleum supply chain.

### 4.4.1 Modeling the crude sector

Let define $W$ as a set of crude oil wells $w \in \{1, 2, ..., W\}$ and $P$ is the set of crude oil products $p \in \{1, 2, ..., P\}$. Let define $G$ as the set of extraction technologies in wells, $I$ the set of storage tanks $i \in \{1, 2, ..., I\}$, and $J$ the set of crude oil markets $j \in \{1, 2, ..., J\}$. $VC^{C}_{pwgt}$ is the decision variable for the extracted quantity of crude oil product $p \in P$ by using the extraction technology $g \in G$ at well $w \in W$ during the period $t \in T$ (bbl/y). $XC^{C}_{pwit}$ is the decision variable for the flow of crude oil product $p \in P$ from well $w \in W$ to storage tanks $i \in I$ during a period $t \in T$ (bbl/y). $SC^{C}_{pit}$ is the decision variable for the quantity of crude oil $p \in P$ kept in the storage tank $i \in I$ at period $t \in T$ (bbl/y). $XCM^{C}_{pijt}$ is the decision variable for the flow of crude oil product $p \in P$ from storage tanks $i \in I$ and to the crude market $j \in J$ during a period $t \in T$ (bbl/y). $XR^{C}_{pwrt}$ is the decision variable for flow of crude oil product $p \in P$ from well $w \in W$ to refinery $r \in R$ during period $t \in T$ (bbl/y). Since we need to develop a future well, a binary variable considers each well to decide which one is located to be active at period T. Let define $BW^{C}_{wt}$ as a binary decision variable that takes a value of 1 if we locate well $w \in W$ at period $t \in T$, 0 otherwise. Also, if we decide to use extracting technology $g \in G$ at period T. Finally, let $BWG^{C}_{wgt}$ the binary decision variable that takes a value of 1 if we use technology extraction $g \in G$ at well $w \in W$ during the period $t \in T$, 0 otherwise. A summary of the crude parameters used to formulate the model is presented in more detail in Appendix I.

### 4.4.2 Modeling the refinery sector

Let define $R$ as a set of refineries $r \in \{1,2,...,R\}$, and $X$ the set of transformation technologies $x \in \{1,2,...,X\}$ Let define $E$ as Set of refinery products $e \in \{1,2,...,E\}$ and $S$ the set of refinery markets $s \in \{1,2,...,S\}$. Let $VR^{R}_{erxt}$ be the decision variable for the production quantity of product $e \in E$ at refinery $r \in R$ using technology $x \in X$ at the period $t \in T$ (bbl/y). Let $XRM^{R}_{erst}$ be the decision variable for the flow of refinery product $e \in E$ from the refinery $r \in R$ to market $s \in S$ at the period $t \in T$ (bbl/y). Let $XRH^{R}_{erht}$ be the decision variable for the flow of refinery product $e \in E$ from the refinery $r \in R$ to petrochemical plants $h \in H$ at the period $t \in T$ (bbl/y). Let $BR^{R}_{rt}$ be a binary variable that takes a value of 1 if we decide to locate use $r \in R$ at period $t \in T$, 0 otherwise. Let $BRG^{R}_{rxt}$ be a Binary variable takes a value of 1 if we use technology transformation $x \in X$ at the refinery $r \in R$ during the period $t \in T$, 0 otherwise. A summary of the refinery parameters used to formulate the model is presented in more detail in Appendix I.

### 4.4.3 Modeling the petrochemical sector

Let define $H$ as the set of petrochemicals plants $h \in \{1,2,...,H\}$, $N$ the set of petrochemicals products $n \in \{1,2,...,N\}$, $Z$ the set of petrochemicals markets $z \in \{1,2,...,Z\}$, and $Q$ the set of transformation technologies used in petrochemicals $q \in \{1,2,...,Q\}$. Let define $K$ the set of storage tanks for petrochemical products $k \in \{1,2,...,K\}$. Let $VH^{H}_{nhqt}$ be the decision variable for the production quantity of petrochemical products $n \in N$ at petrochemical plants $h \in H$ using technology $q \in Q$ at the period $t \in T$ (bbl/y). Let $XH^{H}_{nhkt}$ be the decision variable for the flow of petrochemical products $n \in N$ from petrochemical plants $h \in H$ to the storage tank $k \in K$ at period $t \in T$ (bbl/y). $SH^{H}_{nkt}$ = quantity of petrochemical product $n \in N$ kept in stock at a storage tank $k \in K$ at the period $t \in T$ (bbl/y). $XHM^{H}_{nkzt}$ = flow of $n \in N$ from storage tank

$k \in K$ to market $z \in Z$ at the period $t \in T$ (bbl/y). Let $BH^{H}_{ht}$ be a binary variable that takes a value of 1 if we decide to locate the petrochemical plant $h \in H$ at period $t \in T$, 0 otherwise. Let $BHG^{H}_{hqt}$ be a binary variable that takes a value of 1 if we invest in technology transformation $q \in Q$ in the petrochemical plant $h \in H$ during the period $t \in T$, 0 otherwise.

## 4.5 Model formulation

### 4.5.1 Economic performance

The objective function is to minimize the total cost, including (production, transportation, and storage cost) during the planning period. The model can be expressed in the following equation where $Z^C, Z^R$ *and* $Z^H$ are the costs related to crude oil, refining, and petrochemical sectors, respectively.

$$\text{Min}\, Z = (Z^{C} + Z^{R} + Z^{H}) \tag{4.1}$$

$$\begin{aligned} Z^{C} = (( & \sum_{w}\sum_{t}(LC^{C}_{w} * BW^{C}_{wt}) + \sum_{w}\sum_{g}\sum_{t}(CGW^{C}_{wgt} * BWG^{C}_{wgt}) + \\ & \sum_{p}\sum_{w}\sum_{g}\sum_{t}(EXC^{C}_{pwgt} * VC^{C}_{pwgt}) + \sum_{p}\sum_{w}\sum_{i}\sum_{t}(BRC^{C}_{pwit} * \sum_{w} VC^{C}_{pwgt}) + \\ & \sum_{p}\sum_{i}\sum_{j}\sum_{t}(PMC^{C}_{pijt} * XCM^{C}_{pijt}) + \sum_{p}\sum_{w}\sum_{p}\sum_{t}(PRR^{C}_{pwrt} * XR^{C}_{pwrt}) + \\ & \sum_{p}\sum_{i}\sum_{t}(CSC^{C}_{pit} * SC^{C}_{pit})) \end{aligned} \tag{4.2}$$

$$\begin{aligned} Z^{R} = (( & \sum_{r}\sum_{t}(LR^{R}_{r} * BR^{R}_{rt}) + \sum_{r}\sum_{x}\sum_{t}(CGR^{R}_{rxt} * BRG^{R}_{rxt}) + \\ & \sum_{e}\sum_{r}\sum_{x}\sum_{t}(VTR^{R}_{erxt} * VR^{R}_{erxt}) + \sum_{e}\sum_{r}\sum_{h}\sum_{t}(PRH^{R}_{erht} * XRH^{R}_{erht}) + \\ & \sum_{e}\sum_{r}\sum_{s}\sum_{t}(PRM^{R}_{erst} * XRM^{R}_{erst})) \end{aligned} \tag{4.3}$$

$$Z^{H} = ((\sum_{h}\sum_{t}(LH_{h}^{H} * BH_{ht}^{H}) + \sum_{h}\sum_{q}\sum_{t}(CGH_{hqt}^{H} * BHG_{hqt}^{H}) +$$

$$\sum_{n}\sum_{h}\sum_{q}\sum_{t}(VTH_{nhqt}^{H} * VH_{nhqt}^{H}) + \sum_{n}\sum_{k}\sum_{t}(CSH_{nkt}^{H} * SH_{nkt}^{H}) +$$

$$\sum_{n}\sum_{h}\sum_{k}\sum_{t}(BHK_{nhkt}^{H} * XH_{nhkt}^{H}) + \sum_{n}\sum_{k}\sum_{z}\sum_{t}(BKZ_{nkzt}^{H} * XHM_{nkzt}^{H})) \quad (4.4)$$

### 4.5.2 Environmental performance

The major environmental sustainability issues are; GHG emission, waste, oil spill, and produced water disposal (Sahebi, Nickel et Ashayeri, 2014; Mojarad, Atashbari et Tantau, 2018). However, each of these challenges creates a lot of environmental concerns. Further, this forces the petroleum sector to consider GHG emissions, especially the $CO_2$ impact of their operations, and consider a $CO_2$ mitigation strategy through several activities (production, transportation, storage). The environmental dimension is the second objective function presented in equation 5, which evaluates CO2 emissions from all sectors. The environmental objective function is to minimize the total emission during supply chain activates based on emission factors (EF).

$$E = \text{Min } (E^{C} + E^{R} + E^{H}) \quad (4.5)$$

To calculate $CO_2$ emissions for each petroleum product supplied using equation

$$CO_{2i} = Flow_{i} \times EF_{i} \quad (4.6)$$

**Where:**

$EF_i$ = Emission factor for modes transportation of product between nodes [kg $CO_2$/ km]

$EF_{ij}$ = Emission factor of petroleum product i in plant j [kg $CO_2$/bbl]

$CO_{2i}$ = Annual $CO_2$ emissions expressed (tones $CO_2$/year)

$Flow_i$ = Total annual quantity of flow petroleum products I calculated in (MMbbl/y)

Total emissions in well extraction and transportation at all periods $E^{C} =$

$$\sum_{p}\sum_{w}\sum_{g}\sum_{t}(EFC_{pwg}^{C} * VC_{pwgt}^{C}) + EFLC_{1}^{C} * \sum_{p}\sum_{w}\sum_{i}\sum_{t} XC_{pwit}^{C} + \quad (4.7)$$

$$EFLC_{2}^{C} * \sum_{p}\sum_{w}\sum_{r}\sum_{t} XR_{pwit}^{C} + EFSC_{1}^{C} * \sum_{p}\sum_{w}\sum_{r}\sum_{t} XCM_{pwit}^{C}$$

Total emissions in refinery and transportation at all periods $E^R =$

$$\sum_p \sum_w \sum_x \sum_t (EFR^C_{erx} * VR^R_{erxt}) + EFLR^R_1 * \sum_e \sum_r \sum_h \sum_t XRH^R_{erht} + EFTR^R_1 * \sum_e \sum_r \sum_s \sum_t XRM^R_{erst} \quad (4.8)$$

Total emissions in petrochemical and transportation at period $E^H =$

$$\sum_n \sum_h \sum_q \sum_t (EFH^H_{nhq} * VH^H_{nhqt}) + EFLH^H_1 * \sum_e \sum_h \sum_k \sum_t XH^R_{nhkt} + EFSH^H_1 * \sum_n \sum_k \sum_z \sum_t XHM^H_{nkzt} \quad (4.9)$$

### 4.5.3 Constraints

Constraints represent the demand satisfaction, inbound outbound flow, capacity production, and logical constraints for each sector.

**Crude oil sector constraints**

Crude oil demand satisfaction

$$\sum_i XCM^C_{pijt} = DC^C_{pjt}, \forall p \in P, \forall j \in J, \forall t \in T \quad (4.10)$$

Max and Min Capacity in the well

$$\sum_p \sum_g VC^C_{pwjt} \leq (Cap^C_{wt} * BW^C_w), \forall w \in W, \forall t \in T \quad (4.11)$$

$$(Cap^C_{wt} - Min * BW^C_w) \leq \sum_p \sum_g VC^C_{pwjt}, \forall w \in W, \forall t \in T \quad (4.12)$$

Inventory balance of crude oil at storage tanks

$$SC^C_{pit} = SC^C_{pit-1} + \sum_w XC^C_{pwit} - \sum_j XCM^C_{pijt}, \forall p \in P, \forall i \in I, \forall T > 1 \quad (4.13)$$

Inventory balance of crude oil at tanks for period 1;

$$SC^C_{pi1} = \sum_w XC^C_{pwi1} - \sum_j XCM^C_{pij1}, \forall p \in P, \forall i \in I \quad (4.14)$$

Inventory capacities at storage tanks for crude oil

$$SC^{C}_{pi1} = \sum_{w} XC^{C}_{pwi1} - \sum_{j} XCM^{C}_{pij1}, \forall p \in P, \forall i \in I \tag{4.15}$$

Crude oil production constraints

$$\sum_{g} VC^{C}_{pwgt} = \sum_{i} XC^{C}_{pwit} + \sum_{r} XR^{C}_{pwrt}, \forall p \in P, \forall w \in W, \forall t \in T \tag{4.16}$$

Capacity in the well

$$\sum_{p} VC^{C}_{pwgt} \leq Cap^{C}_{wt}, \forall w \in W, \forall t \in T \tag{4.17}$$

Logical constraints for wells

$$\sum_{g} \sum_{t} BWG^{C}_{wgt} \leq (BigM^{C} * BW^{C}_{w}), \forall w \in W \tag{4.18}$$

$$\sum_{g} \sum_{t} BWG^{C}_{wgt} \geq BWG^{C}_{wgt-1}, \forall w \in W, g \in G, \forall T > 1 \tag{4.19}$$

$$\sum_{g} BWG^{C}_{wgt} = 1, \forall w \in W, \forall t \in T \tag{4.20}$$

$$\sum_{g} BWG^{C}_{wgt} = 1, \forall w \in W, \forall t \in T \tag{4.21}$$

$$\sum_{p} VC^{C}_{pwgt} \leq (BigM^{C}_{wt} * BW^{C}_{w}), \forall w \in W, \forall g \in G, \forall t \in T \tag{4.22}$$

$$\sum_{p} VC^{C}_{pwgt} \leq (BigM^{C}_{wt} * BW^{C}_{w}), \forall w \in W, \forall g \in G, \forall t \in T \tag{4.23}$$

**Refinery sector constraints**

Refinery demand satisfaction

$$DR^{R}_{est} = \sum_{r} XRM^{R}_{rest}, \forall e \in E, \forall s \in S, \forall t \in T \tag{4.24}$$

Inbound flow of crude to produce refinery product

$$\sum_{x} VR^{R}_{erxt} = \gamma^{R}_{rpe} * \sum_{w} XR^{R}_{pwrt}, \forall r \in R, \forall p \in P, \forall e \in E, \forall t \in T \tag{4.25}$$

Outbound flow constraints from the refinery

$$\sum_{x} VR^{R}_{erxt} \geq \sum_{s} XRM^{R}_{erst} + \sum_{h} XRH^{R}_{erht}, \forall e \in E, r \in R, \forall t \in T \tag{4.26}$$

Max and Min Capacity in the refinery

$$\sum_e \sum_x VR^R_{est} \le (Cap^R_{rt} * BR^R_r), \forall r \in R, \forall t \in T \tag{4.27}$$

$$\sum_e \sum_x VR^R_{est} \ge (Cap^R_{rt} - Min * BR^R_r), \forall r \in R, \forall t \in T \tag{4.28}$$

Logical constraints for refinery

$$BRG^R_{rxt} = BRG^R_{rxt-1}, \forall r \in R, \forall x \in X, \forall T > 1 \tag{4.29}$$

$$BRG^R_{rxt} = 1, \forall r \in R, \forall x \in X, \forall t \in T \tag{4.30}$$

$$\sum_e VR^R_{erxt} \le (BigM^R * BRG^R_{rxt}), \forall r \in R, \forall t \in T, x \in X \tag{4.31}$$

$$\sum_x \sum_t BRG^R_{rxt} \le (Big\_MR * BR^R_r), \forall r \in R \tag{4.32}$$

**Petrochemical sector constraints**

Petrochemical demand satisfaction

$$\sum_k XHM^H_{nkzt} = DH^H_{nzt}, \forall n \in N, \forall z \in Z, \forall t \in T \tag{4.33}$$

Flow of petrochemical

$$\sum_q VH^H_{nhqt} = \sum_k XH^H_{nhkt}, \forall n \in N, \forall h \in H, \forall t \in T \tag{4.34}$$

Outbound flow from petrochemical

$$SH^h_{nk1} = \sum_h XH^H_{nhk1} - \sum_z XHM^H_{nkz1}, \forall n \in N, \forall k \in K \tag{4.35}$$

Sending refinery product (E4) to petrochemical

$$(1/3 * \sum_r XRH^H_{4rht}) = \sum_q VH^H_{4hqt}, \forall n \in N, \forall h \in H, \forall t \in T \tag{4.36}$$

No sending refinery product (E1) to petrochemical

$$XRH^H_{1rht} = 0, \forall h \in H, \forall r \in R, \forall t \in T \tag{4.37}$$

No sending refinery product (E2) to petrochemical

$$XRH_{2rht}^{H} = 0, \forall h \in H, \forall r \in R, \forall t \in T \tag{4.38}$$

No sending refinery product (E3) to petrochemical

$$XRH_{3rht}^{H} = 0, \forall h \in H, \forall r \in R, \forall t \in T \tag{4.39}$$

Inventory balance for petrochemical at storage tanks

$$SH_{nkt}^{h} = SH_{nkt-1}^{h} + \sum_{h} XH_{nhkt}^{H} - \sum_{z} XHM_{nkzt}^{H}, \forall n \in N, \forall k \in K, \forall T > 1 \tag{4.40}$$

Inventory balance of petrochemical at tanks for period 1

$$SH_{nk1}^{h} = \sum_{h} XH_{nhk1}^{H} - \sum_{z} XHM_{nkz1}^{H}, \forall n \in N, \forall k \in K \tag{4.41}$$

Max Capacity of petrochemical

$$\sum_{n} \sum_{q} VH_{nhzt}^{h} \leq Cap_{ht}^{H}, \forall h \in H, \forall t \in T \tag{4.42}$$

Min Capacity of petrochemical

$$Cap_{ht}^{H} - Min \leq \sum_{n} \sum_{q} VH_{nhzt}^{h}, \forall h \in H, \forall t \in T \tag{4.41}$$

Inventory capacities at storage tanks for petrochemical

$$SH_{nkt}^{H} \leq SH_{nkt}^{\max}, \forall n \in N, \forall k \in K, \forall t \in T \tag{4.43}$$

Petrochemicals production constraints

$$\sum_{q} VH_{nhqt}^{H} \geq \sum_{k} XH_{nhkt}^{H}, \forall n \in N, \forall h \in H, \forall t \in T \tag{4.44}$$

Logical constraints for petrochemicals

$$\sum_{q} \sum_{t} BHG_{hqt}^{H} \leq (BigM^{H} * BH_{h}^{H}), \forall h \in H \tag{4.45}$$

$$\sum_{q} \sum_{t} BHG_{hqt}^{H} \geq BHG_{hqt-1}^{H}, \forall h \in H, \forall q \in Q, \forall T > 1 \tag{4.46}$$

$$\sum_{q} BHG_{hqt}^{H} = 1, \forall h \in H, \forall t \in T \tag{4.47}$$

$$\sum_{n} VH_{nhqt}^{H} \leq (BigM^{H} * BH_{h}^{H}), \forall h \in H . \forall q \in Q, \forall t \in T \tag{4.48}$$

Business rules specific to the case study

Flow of refined product 4 between refinery and petrochemical plants

$$1/3*(\sum_{r} XRH_{4rht}^{R}) = \sum_{q} VH_{1hqt}^{H}, \forall h \in H, \forall t \in T \tag{4.49}$$

There is now flow for refined products 1, 2, and 3 between refinery and petrochemical plants

$$XRH_{1rht}^{R} = 0, \forall h \in H, r \in R, \forall t \in T \tag{4.50}$$

$$XRH_{2rht}^{R} = 0, \forall h \in H, r \in R, \forall t \in T \tag{4.51}$$

$$XRH_{3rht}^{R} = 0, \forall h \in H, r \in R, \forall t \in T \tag{4.52}$$

## 4.6 Multiobjective optimization

A multiobjective problem arises in the previous formulation and is generally formulated as follows: *"The ε-constraint method is considered a solution procedure in this paper because the decision-maker doesn't need to articulate a prior preference for the objective. Also, there are no specific conditions to achieve the solutions, and the method is simple since it transforms the multiobjective problem into a single-objective optimization problem. Thus, one objective (f1) is selected for optimization. The remaining objectives(f 2) are reformulated as constraints"* (Lahri, Shaw et Ishizaka, 2021). As in figure 4.2

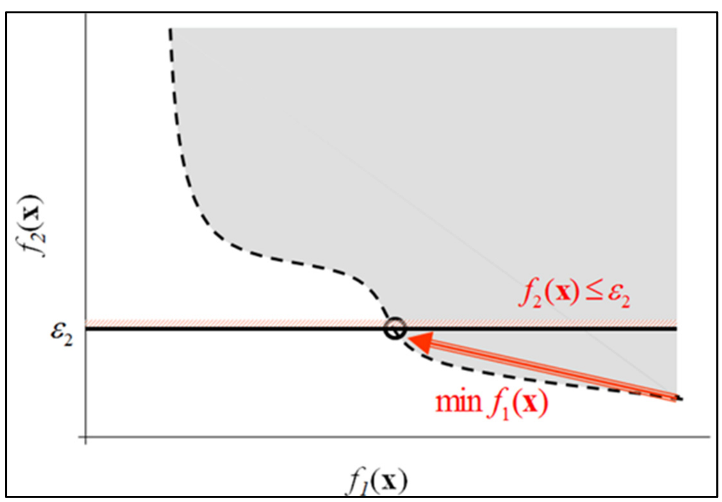



Figure 4.2 The ε-constraint method

To solve the previously formulated model (sub-section 3.4) using the ε-constraint method, the objective, *Z*, is selected for the optimization. The objective function E is reformulated as a constraint. By progressively changing the constraint values, ε, the Pareto-frontier curve is obtained. By calculating the Pareto-frontier's extremes, the values and the range of objective *E* are selected accordingly.

## 4.7 Conclusion

In this chapter, a novel mixed-integer linear programming model is presented based on the economic and environmental dimensions to evaluate the impact of introducing a stringent environmental regulation limiting greenhouse gas emissions. This model aims to minimize the crude, refinery, and petrochemical sectors total cost to meet environmental standards and regulations and examine the impact of incorporating investment decisions in different carbon emission reduction options. The proposed model is tested with real data based on the Libyan petroleum industry. Computational results will be analyzed and demonstrate model capabilities to deal with the trade-off between the total cost and the petroleum sector's environmental issues.

# CHAPTER 5

# EXPERIMENTS AND RESULTS

## 5.1 Introduction

In this chapter, we will present the solution approach and numerical results of the eco-efficient model. Besides, comparisons were made in three scenarios. The objective is to present the different carbon emission reduction options and evaluating the supply chain performance based on the economic and environmental dimensions. Sensitivity analysis will present in uncertainty data collection, which is the case of environmental regulations, to help us for validation of the main findings. As a final note, this section describes the solution procedure for the case study to represent the crucial mitigation strategies for different scenarios. The model is solved using the LINGO 19.0 from LINDO systems. The proposed model's efficiency has been tested using the Libyan supply chain covering all petroleum sectors (upstream, midstream, and downstream).

## 5.2 Case description and data collection

Most of the data has been collected with the (NOC) collaboration at different levels (crude oil, refinery, petrochemical sectors) most of them were confidential. Other confidential data were estimated using official websites, published reports, previous studies, and online platforms. The sources of data and environmental information are very limited because the government does not have long-established institutions to deal with environmental issues. In terms of data collection was obtained from annual reports from the National Oil Corporation in Libya. Therefore, we calcified the data regarding each sector. Data on the capital and operating costs of the process units are obtained from (NOC) and some petroleum reports.

The Libyan government distributed the products according to the annual demand. The supply chain network is composed of several oil wells. In this study, we aggregate the wells into five basins. Each basin has the same characteristics (depth and rocket type) and using the same extracting technology. The crude oil is extracted from five (5) onshore basins and two (2) offshore platforms and transported via pipelines to feed the local refineries and storage tanks.

The crude oil exported to satisfy the international market as agreed in the OPEC quota. Figure 3 shows the crude oil market distribution. Moreover, the figure shows the distribution of global versus local market demands for crude oil. Furthermore, five refineries are located in different regions (Zawia, Ra's Lanuf, Brega, Tobruk, and Sarir) with 380,000 bbl/day production capacity. Refinery products like Gasoline, Naphtha, Jet fuel, and LPG (Liquefied Petroleum Gas) are transported to the local market by trucks and used to satisfy the local demand Abdilahi et al., (2018). The remaining quantities are used as a feedstock for two (2) local petrochemical plants to produce Ethylene, Methanol, Ammonia, and Urea. The petrochemical products are used to satisfy local industries and international demand Elhawari, (2019). As mentioned earlier, we considered three modes of transportation in this study: pipeline, maritime, and truck to deliver the products to each node. The transportation cost varies with the distance over which the products must be transferred.

In this study, we consider only the direct emissions from certain activities that count as a significant source of $CO_2$ emissions in each sector. During the wells' extracting activities, $CO_2$ is released from using devices, including engines, construction devices, and heaters generated by fuel diesel Vypovska et al., (2018). The emission intensity for Libya oil extraction is below the world average. The world average is around 18 kg $CO_2$ / bbl, but it is only 10 kg $CO_2$ /bbl in Libya Waxman et al., (2020); Masnadi et al.,( 2018); Jing et al., (2020). Table-A II-1, Table-A II-2, and Table-A II-3 in Annex II provide emission factors for extraction, refinery and petrochemical activities. Also, the emissions factors for transportation activities are provided in Table-A III-1 in Annex III ( Azzolina et al., 2016; Choquette-Levy et al., 2018; Gordon et al., 2015).

In the experimentation of the proposed model, three scenarios have been developed. The first scenario (Baseline) is when we optimize the petroleum supply chain without considering the $CO_2$ reduction objective (see Annex IV, Table-A IV). In the second scenario, we assume that only carbon capture and storage (CCS) technology is activated to achieve the $CO_2$ reduction targets and mitigate the environmental damage (see Annex V, Table-A V-1). Finally, in the third scenario, we consider the possibility of long-term investment in green technologies (efficiency in operations and energy efficiency) to meet energy demand and sustainability challenges (see Annex IV, Table-A IV, Annex V, Table-A V-1, and Annex VI, Table VI-1 for related data details).

Green energy technologies have become the tremendous potential emission reduction to avoid carbon emission charges on the energy alternative (Jia, Dai et Wang, 2018). Therefore, this study will focus on solar (green) energy as it is the best renewable energy source to be integrated with conventional energy into the oil sector in the region (Halabi, Al-Qattan, et al.-Otaibi, 2015; Pickl, 2019). The baseline optimization model has 5,239 variables and 3827 constraints. The average run-time per scenario with the default LINGO solver settings was 6 s. Computation time for the problem is negligible, and therefore is not further discussed.

## 5.3 Baseline scenario

The baseline scenario's objective is to meet each product's demand requirement and identify the $CO_2$ emission contribution of each level on the petroleum sector and the cost related to that. The results are shown in Table 5.1 and compare costs and the $CO_2$ emissions contributions of the different oil sectors.

Table 5.1 Baseline scenario of different sectors

| **Sector** | **Total cost (M $)** | **Total cost (%)** | **Total $CO_2$ emissions (KT $CO_2$)** | **Total $CO_2$ emissions (%)** |
|---|---|---|---|---|
| Crude oil | 69,539 | 54 | 135,096 | 73 |
| Refinery | 33,638 | 26 | 34,506 | 19 |
| Petrochemical | 1,986 | 2 | 2,885 | 2 |
| Transportation | 22,509 | 18 | 11,927 | 6 |
| Total (20 years) | **127,672** | 100 | **184,415** | 100 |
| **Average** | **6,384 (M$/year)** | | **9,222 KT $CO_2$ /year** | |

The crude sector accounts for a total cost of 69,539 M$ (54 %) and 135,096 KT of $CO_2$ (73% of the total emissions). The refinery sector accounts for 34,505 KT $CO_2$ (19% of total emissions). The three sectors' total $CO_2$ emission is 184,415 KT $CO_2$ with a total cost of 127,672 M$. The results obtained for the baseline scenario are in line with the recent studies that report the cost and the $CO_2$ emission per bbl in the region (Etelawi, Blatner et McCluskey, 2017b; Jing et al., 2020a; Etelawi, Blatner et McCluskey, 2017a; Jing et al., 2020a). For this, we can observe that the cost of producing one bbl of crude is $8.59, as shown in Figure 5. The average cost of refined products is $14.31 / bbl and $16.20 to produce one bbl of ethylene.

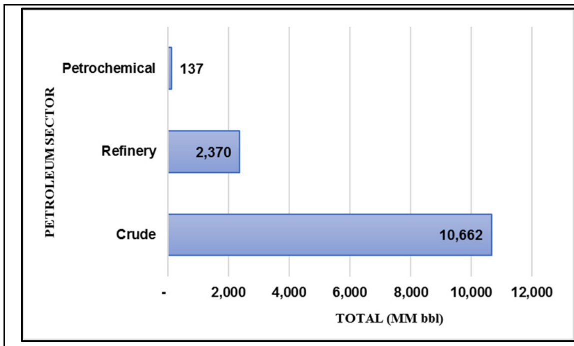



Figure 5.1 Total production quantity (MM bbl)

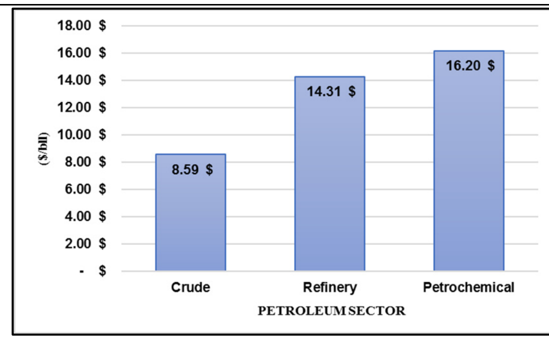



Figure 5.2 Production cost/bbl

Further, the direct $CO_2$ emissions from each petroleum sector are presented in Figures 5.1 and 5.2; production crude oil in upstream operations accounts for the highest emissions because crude oil extraction energy-intensive production methods to extract crude oil, especially in offshore platforms.

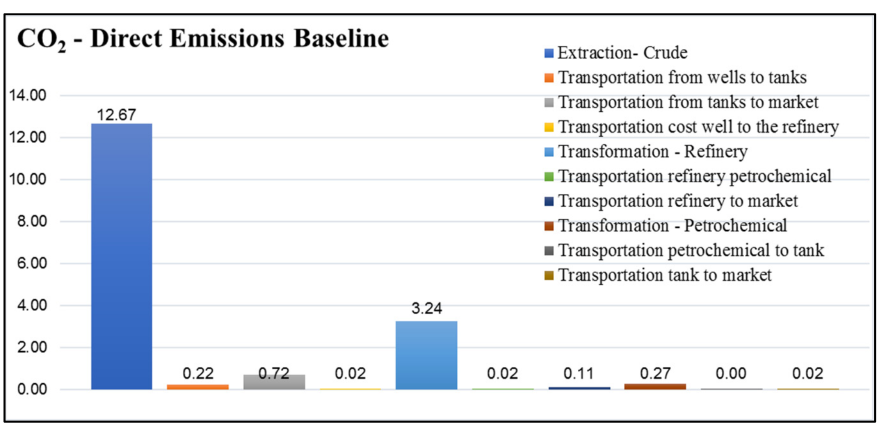



Figure 5.3 Life cycle of direct $CO_2$ emissions (kg $CO_2$/bbl)

Also, the refinery sector is massively emitted $CO_2$ because of the complex process systems that synthesize several products while utilizing large amounts of energy and hydrogen for hydrotreatment processes. Figure 5.3 shows the Life cycle assessment of direct $CO_2$ emissions (kg $CO_2$/bbl).

Figures 5.4 and 5.5 demonstrates the detail about transportation cost and $CO_2$ emissions. Although cost from pipeline transportation systems is the most dominant since it represents the petroleum industry's primary mode, the maritime transportation system generates the highest emission level. The lack of flexibility in the petroleum transportation network makes the potential reduction from transportation activities very limited (Elmansouri et al, 2020).

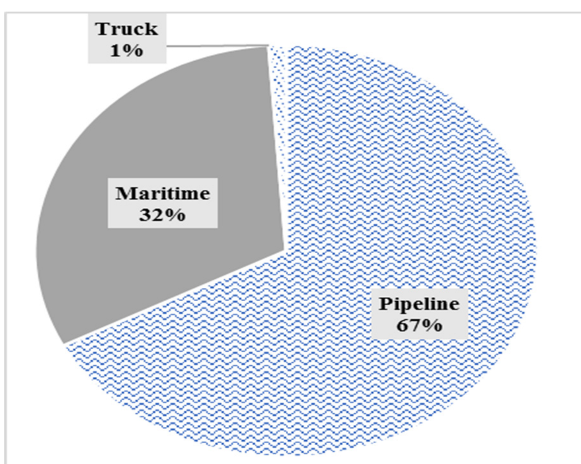



Figure 5.4 Modes of transportation cost comparison

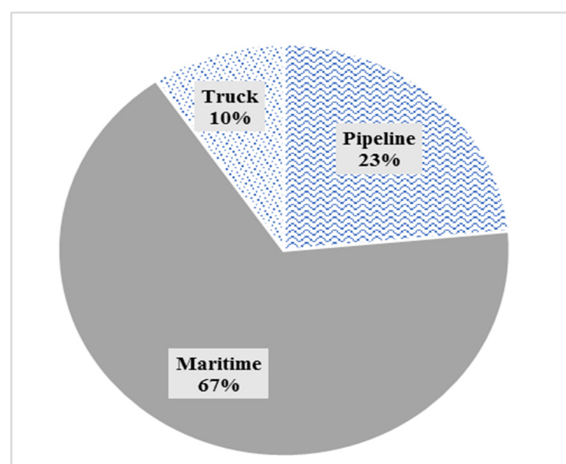



Figure 5.5 Modes of transportation $CO_2$ comparison

## 5.4 Carbon capture and storage scenario

According to Table 5.1, the total $CO_2$ emission for the Baseline scenario is 184,415 KT $CO_2$ in total (an average of 9,220 KT $CO_2$/year). In the first scenario, we evaluate carbon capture technology's impact on reducing $CO_2$ in each sector's activities. With the implementation of carbon capture and storage (CCS) projects, it is possible to reduce $CO_2$ emissions by more than 32%. Table 3 summarizes the total $CO_2$ emissions and the total costs for all sectors for different $CO_2$ reduction target scenarios. We can observe that the supply chain cost increased for all scenarios compared to the Baseline. For instance, with a 32% $CO_2$ emissions reduction objective (scenario CCS-7), the total cost increases by 10.70% and brings the total cost to141,328 M$. More detailed results are available in Table-A V-1 in Annex V.

Table 5.2 Capture scenario of different $CO_2$ reduction versus Baseline

| Scenario | $CO_2$ Reduction target (%) | Total cost (M $) | Cost increase % | Total emissions KT $CO_2$ | $CO_2$ decrease (%) | Abatement cost ($/ T $CO_2$) | Crude cost / bbl ($/bbl) | Refinery cost / bbl ($/bbl) | Petrochemical cost / bbl ($/bbl) |
|---|---|---|---|---|---|---|---|---|---|
| **Baseline** | 0 % | 127,671 | 0 | 184,415 | 0 | - | 8.59 | 14.31 | 16.20 |
| **CCS-1** | 5 % | 127,753 | 0.06% | 170,314 | 7.75% | 5.82 | 8.59 | 14.31 | 16.20 |
| **CCS-2** | 10 % | 128,028 | 0.28% | 164,074 | 11.13% | 17.55 | 8.62 | 14.31 | 16.20 |
| **CCS-3** | 15% | 128,173 | 0.39% | 153,177 | 17.03% | 16.07 | 8.63 | 14.31 | 16.20 |
| **CCS-4** | 20 % | 128,488 | 0.64% | 138,335 | 25.07% | 17.73 | 8.88 | 14.31 | 16.21 |
| **CCS-5** | 30 % | 129,231 | 1.22% | 133,925 | 27.46% | 30.90 | 9.17 | 14.31 | 16.22 |
| **CCS-6** | 31 % | 134,377 | 5.25% | 127,385 | 30.92% | 117.59 | 9.18 | 14.48 | 16.28 |
| **CCS-7** | 32% | 141,328 | 10.70% | 124,502 | 32.56% | 227.95 | 9.18 | 17.22 | 18.94 |
| **CCS-8** | **33%** | **Unfeasible** | | | | | | | |

Using the results obtained from Table 5.2, the Pareto frontier presented in Figure 5.6 (a) demonstrates the economic and environmental objectives conflict. Figure 5.6 (b) shows the marginal abatement cost (MAC), which measures the cost of reducing one tone of $CO_2$ for each scenario. Indeed, with scenario CCS-7, the MAC can reach $227. For this case, the implementation of CCS for all sectors is necessary (see Annex V, Table-A V-1). However, if we activate CCS projects only for the crude sector, we can achieve up to 30% of $CO_2$ reduction (CCS-5). In this specific scenario, the total cost increase by only 1.22%, and the MAC will be around $30.

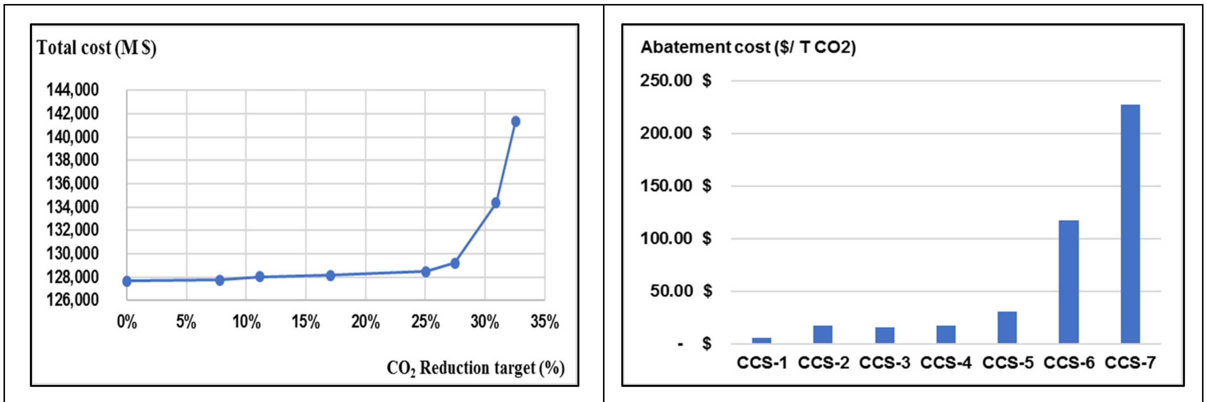



Figure 5.6 Total and abatement costs for CCS scenarios

These results can be explained by the fact that CCS project implementation at refinery and petrochemical plants cannot be economically viable options given the low production level in these plants Chan et al., (2016). As in figure 5.7

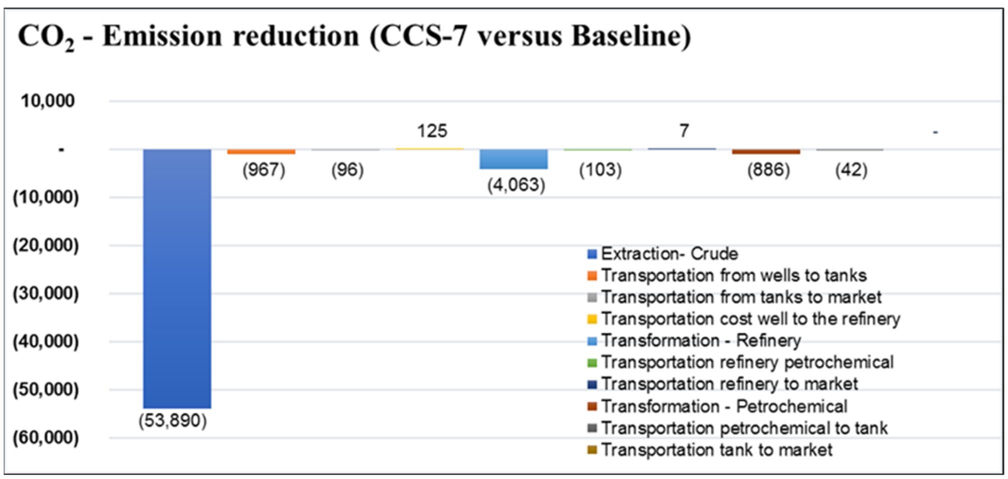



Figure 5.7 Comparison in emission reduction
(CCS-7 and Baseline scenarios (kg $CO_2$/bbl)

To achieve this total abatement objective, we observe significant investment in the crude and refinery sectors. Figure 5.8 compares cost and $CO_2$ perspectives between the baseline and CCS-7 scenarios for each sector.

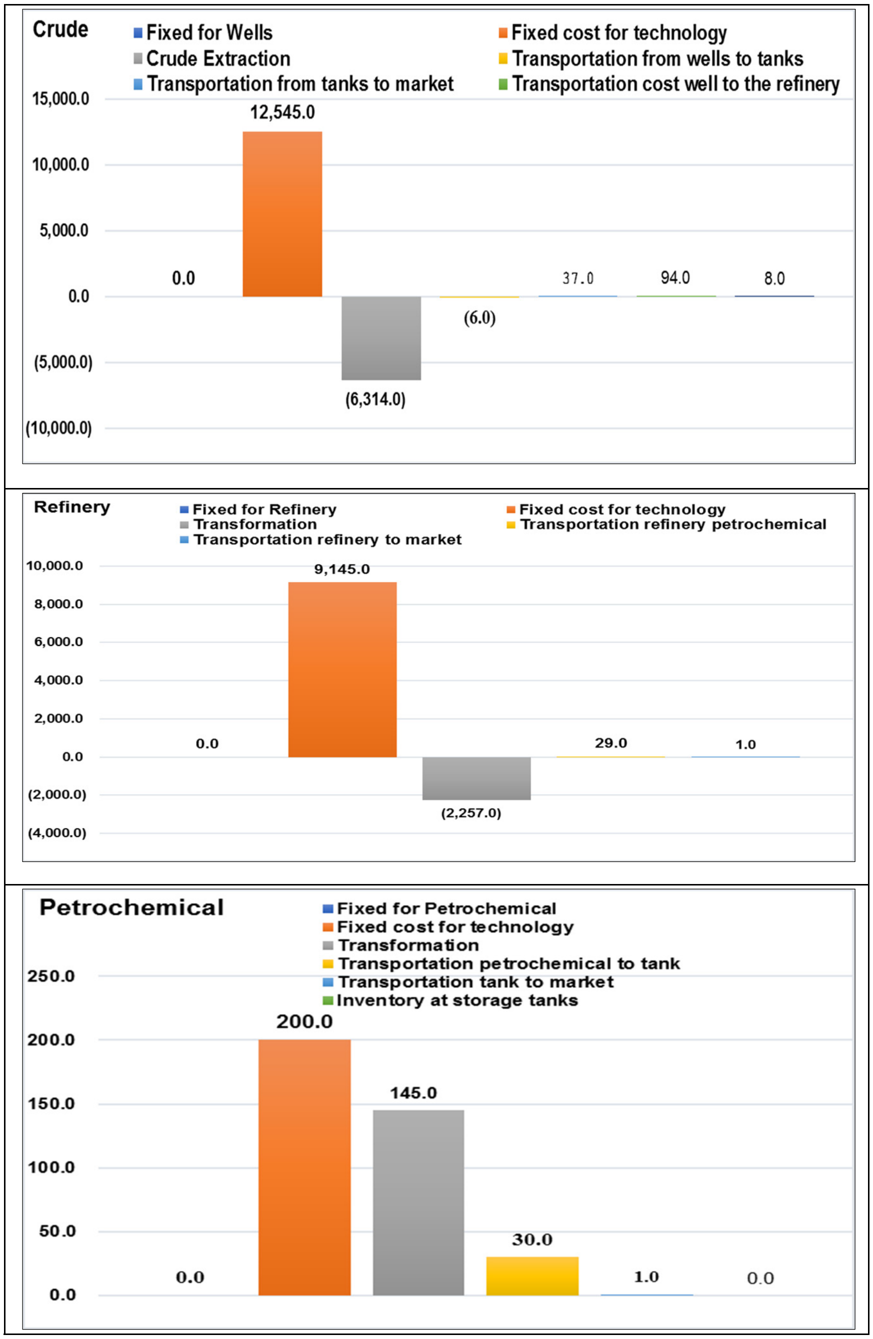
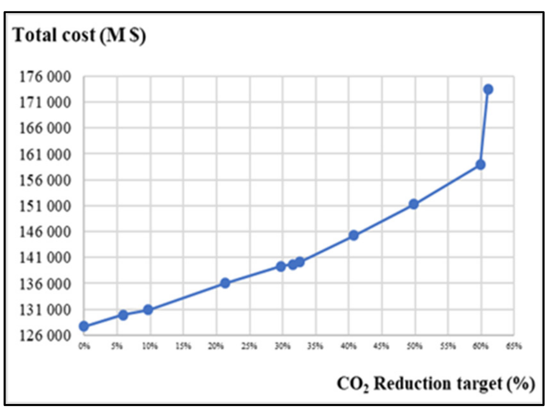



Figure 5.8 Comparison of cost and $CO_2$ emission baseline and CCS-7 scenarios in different sectors

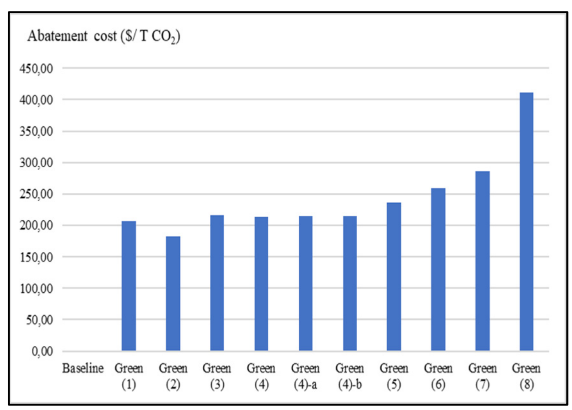
Simultaneously, we observe a reduction in the extraction and transformation costs resulting from more efficiency in extracting crude and the refinery transformation. On the other hand, for the petrochemical sector, we witness a cost increase for all activities. Finally, the principal reduction in $CO_2$ emission is observed for crude extraction activities, representing 73% of the total emission reduction (see Annex V, Table-A V-1).

### 5.5 Green energy scenario

For the third scenario, we consider investing in solar energy to be used during the extraction and production activities in refinery and petrochemical plants. Table 5.3 shows the results with the details on emissions reduction by implementing green (solar) technologies. It indicates that this option can help the petroleum industry in Libya achieve up to a 62% reduction of $CO_2$ emissions (Green-8 scenario), which increases the total cost by 35.91%, which is in line with similar studies in the literature (Alnifro et al., 2017; Alsharif, Yahya et Geem, 2020; Jing et al., 2020). Also, the Pareto frontier in Figure 5.8 (a) demonstrates the set of Pareto optimal solutions (those that are not dominated by any other feasible solutions). Also, Figure 5.8 (b) determines the marginal abatement costs for different $CO_2$ reduction target scenarios.




a) Pareto frontier




b) Abatement costs

Figure 5.9 Total and abatement costs for green scenarios

Figure 5.9 presents the comparison cost and $CO_2$ perspective between the baseline and green 8 (GR-8) scenarios, which generate a 61.47% reduction in $CO_2$, but a cost increase to 35.91%. It needs significant investment in the crude (upstream) and refinery sectors (midstream) to achieve the abatement objective. For more details, (see Annex VI, Table-A VI-1).

Table 5.3 Green reduction scenarios

| Scenario | $CO_2$ Reduction target (%) | Total cost (M $) | Cost increase (% ) | Total emissions KT $CO_2$ | $CO_2$ decrease (%) | Abatement cost ($/ T $CO_2$) | Crude cost / bbl ($/bbl) | Refinery cost / bbl ($/bbl) | Petrochemical cost / bbl ($/bbl) |
|---|---|---|---|---|---|---|---|---|---|
| Baseline | 0 % | 127,671 | 0.00% | 184,415 | - | - | 8.59 | 14.31 | 16.10 |
| GR-1 | 5 % | 129,871 | 1.72% | 171,665 | 6.91% | 172.55 | 8.79 | 14.31 | 16.20 |
| GR-2 | 10 % | 130,889 | 2.52% | 164,699 | 10.69% | 163.22 | 8.89 | 14.31 | 16.21 |
| GR-3 | 20% | 136,071 | 6.58% | 143,482 | 22.20% | 205.21 | 9.37 | 14.31 | 16.20 |
| GR-4 | 30 % | 139,271 | 9.09% | 128,099 | 30.54% | 205.98 | 9.67 | 14.31 | 16.20 |
| GR-4a | 31% | 139,710 | 9.43% | 126,269 | 31.53% | 207.05 | 9.70 | 14.38 | 16.49 |
| GR-4b | 32% | 140,089 | 9.73% | 124,439 | 32.52% | 207.05 | 9.68 | 14.64 | 16.21 |
| GR-5 | 40 % | 145,298 | 13.81% | 107,944 | 41.47% | 230.51 | 10.24 | 14.31 | 16.20 |
| GR-6 | 50% | 151,244 | 18.46% | 91,500 | 50.38% | 253.70 | 10.80 | 14.31 | 16.21 |
| GR-7 | 60% | 158,922 | 24.48% | 73,200 | 60.31% | 281.00 | 11.38 | 14.66 | 20.68 |
| GR-8 | 62% | 173,744 | 36,11% | 69,900 | 62,09% | 402,33 | 11,38 | 20,51 | 26,05 |
| GR-9 | 63% | Unfeasible | | | | | | | |

More results for emission reduction in figure 5.10 for the Green-8 scenario compare with the baseline scenario. We can observe that most of the reduction comes from the crude sector and refinery. The supply chain cost increased for all scenarios compared to the baseline.

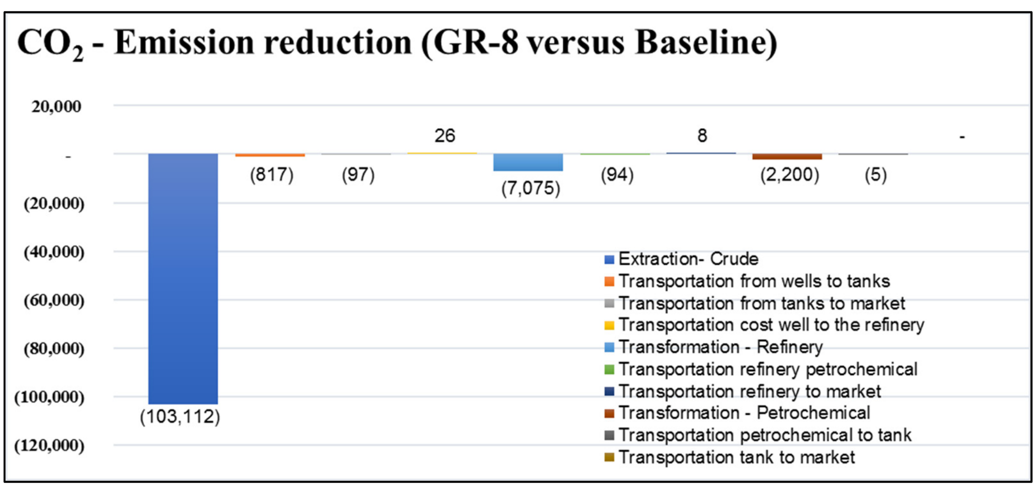



Figure 5.10 Comparison in emission reduction
GR-8 and Baseline scenarios (kg $CO_2$/bbl)

Figure 5.11 compares cost and $CO_2$ perspectives between the baseline and GR-8 scenarios in different sectors for each sector.

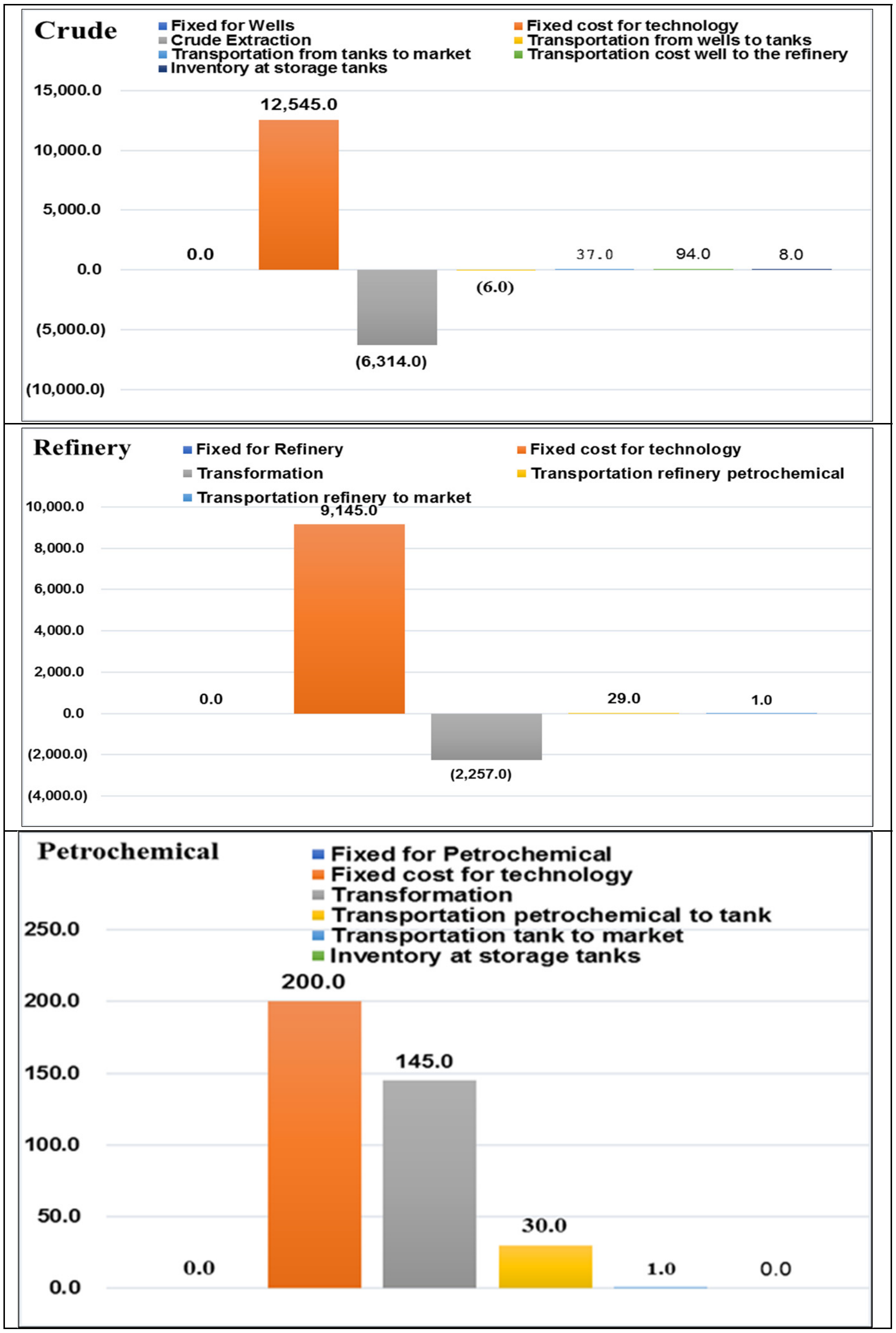
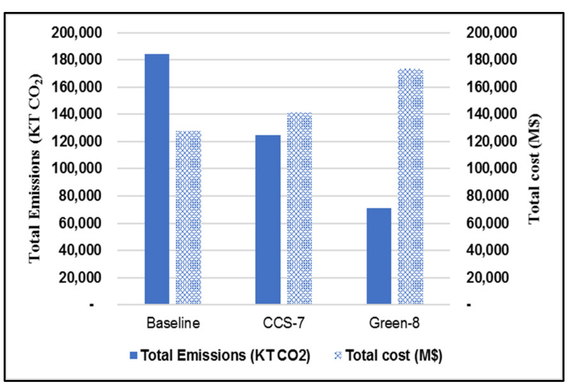


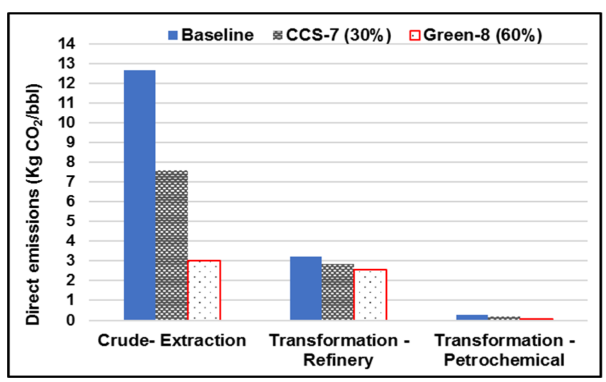

Figure 5.11 Comparison between the GR-8 and Baseline scenarios in different sectors

To achieve the total abatement objective, we observe significant investment in the crude and refinery sectors, but for the transformation cost for the petrochemical sector will increase, that is mean less investment is better.

Also, we observe the amount of emission reduction reduced from 50 kg CO2/bbl in CCS to 103 kg CO2/bbl in green. As a final note, Figures 5.12 (a) and (b) show the comparison between the three scenarios. Failing the mitigation strategies for scenarios 2 and 3 would result in the models' infeasibility in reduction target of more than % 32 in capture technology and 62% in green technology. By far, using green energy in the oil industry might achieve the reduction emissions 63 %, but in the CCS, we will not reduce more than 32 % (Alhajri et al., 2013; Chan et al., 2016; Kangas, Nikolopoulou et Attiya, 2013; Nguyen et al., 2016). Therefore, it is crucial to propose appropriate mitigation strategies depending on the stringency of environmental regulations.




a) Total emission ($KTCO_2$)




b) Direct emissions for production (Kg $CO_2$/bbl)

Figure 5.12 Total cost and total $CO_2$ emissions comparison

There is a trade-off relationship between the emission reduction and the cost. This provides information on how much impact a specific increase in cost would have on the supply chain's performance with respect to the environment. In the transportation activities, we can note that increase the pipeline between Baseline and capture, we need to see the difference and the shift. As in table 5.4. Green technology has a high investment cost compare to capture, and we can achieve a 60% reduction in $CO_2$ emissions for long-term objectives, but it has a high impact on the total cost of the supply chain (Jia, Dai et Wang, 2018). So, we can get less cost with high emissions reductions for the Baseline. Moreover, this is linked to the price of the bbl. If it is a low price, we cannot go for a lower reduction, but we can assume OPEC quota for more demand in the future (John, 2018). However, if the price is high, then the government has to look for more reductions. In most solar energy technologies, the capital cost is around 80% of the total cost (Jia et al.,2018) (Abureden, 2014), but it has a high return rate. The only issues are how the estimate of the energy requirements makes a complicated process.

Table 5.4 Transportation cost and $CO_2$ emissions comparison

| Activities | Transportation Modes | Baseline | CCS-6 | Green-8 |
|---|---|---|---|---|
| Cost M $ | Pipeline | 15,166 | 15,312 | 15,201 |
| | Maritime | 7,093 | 7,131 | 7,130 |
| | Truck | 250 | 251 | 252 |
| | Total | 22,509 | 22,694 | 22,583 |
| $CO_2$ K Ton | Pipeline | 2,804 | 1,818 | 1,913 |
| | Maritime | 7,982 | 7,886 | 7,885 |
| | Truck | 1,141 | 1,148 | 1,149 |
| | Total | 11,927 | 10,852 | 10,947 |

## 5.6 Sensitivity analysis and managerial insights

Sensitivity analysis is essential when planning in an uncertain environment which is the case of environmental regulations. It will help in the validation of the main findings. However, the data collection phase is challenging, and sometimes it is impossible to get accurate information for some parameters. The data quality varies from different sources, especially related to cost and emission factors, given the various methods and approaches used in the calculation.

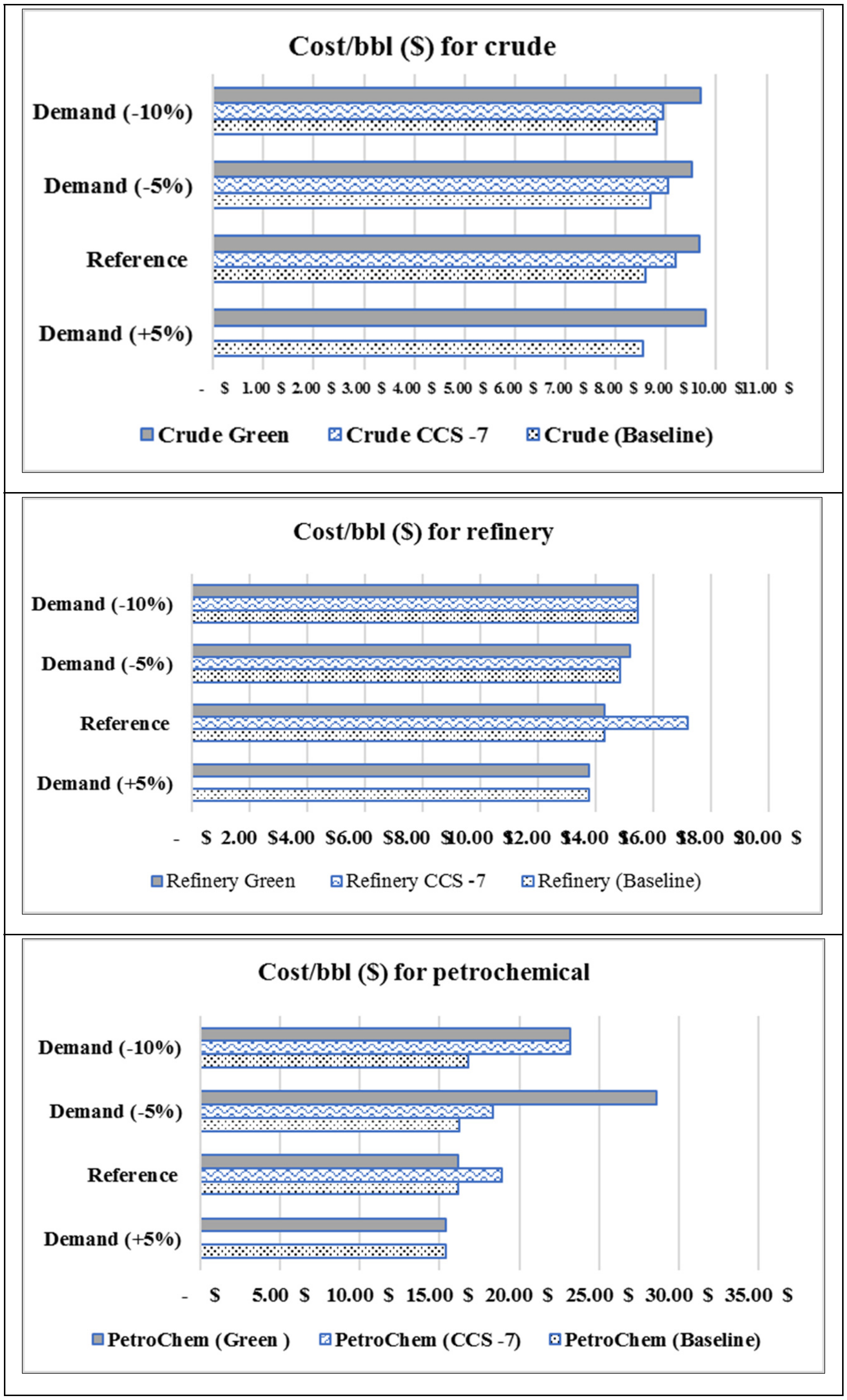



Figure 5.13 Cost analysis with demand variation

For instance, we observe a significant variation in the estimation of emission factors, leading to high levels of uncertainty (Azzolina et al., 2016; Nassar, Aissa et al. sadi, 2017; Gordon et Feldman, 2016; Hirshfeld et Kolb, 2012; Holmgren et Sternhufvud, 2008). sensitivity analysis for demand. Since we consider a planning horizon of 20 years, we include a sensitivity analysis regarding future demand estimation (Dale et Fattouh, 2018). We consider scenarios where the reduction target of $CO_2$ emission is 30 % for both CCS and green options to see this variation's impact. As shown in Figure 5.11 to achieve the target of 30% while respecting the entire demand. If the demand increases by only 5%, reaching the reduction target using green energy is possible. The CCS implementation is not capable of achieving this objective. For the baseline scenario and with a demand increase of 5%, we witness a decrease in the cost per bbl for crude (-0.47%), refinery (-3.56%), and petrochemicals (-0.45%) which can be explained by the increase in the efficiency of supply chain activities.

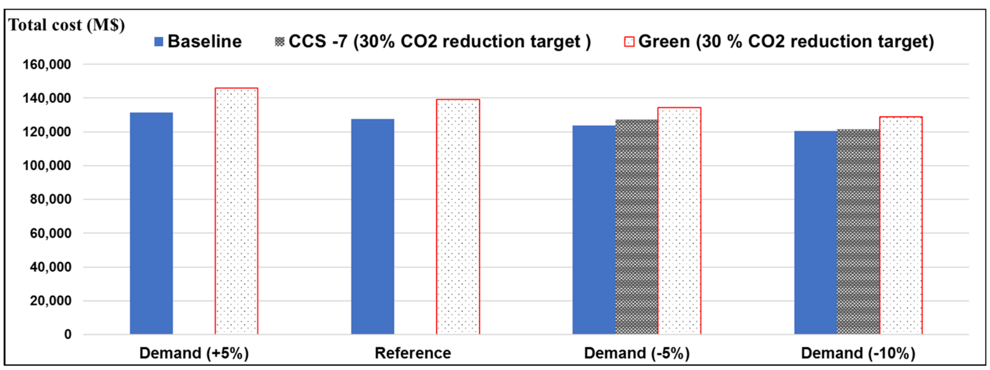



Figure 5.14 Cost analysis with demand variation

For the green option, with the significant investment mainly in the crude sector to reduce $CO_2$ emission, the crude oil cost/bbl changed from \$9.67/bbl to \$9.78/bbl, representing an increase of 1.14% (see Annex VIII, Table-A VIII, scenario GR-4). Nevertheless, the refinery and petrochemical products observe a decrease in the cost/bbl (- 3.56% for refined and -5.12% for petrochemicals). We also explore the impact of demand decrease by 5% and 10%. We witness a cost/bbl increase for crude, refinery, and petrochemical products in both situations for the baseline scenario. The maximum is observed for refinery products with a rise of 8.11% when the demand decreases by 10% (see Table 5.5).

Furthermore, when demand decreases, we can obtain solutions for the two scenarios (CCS and Green). The cost /bbl for the crude decline could be explained by the less need for investment in wells' carbon abatement technologies. The only exception is observed when the demand decreases by 10%. Indeed, the cost/bbl for crude increases by 0.31%. Finally, we see a similar change for refined and petrochemical products when demand decreases. Indeed, this situation brings automatic $CO_2$ reduction and consequently less investment.

Table 5.5 Cost /bbl sensitivity analysis

| **Sector** | **Crude (cost/bbl)** | | | **Refinery (cost/bbl)** | | | **Petrochemical (cost/bbl)** | | |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | Baseline | CCS | Green | Baseline | CCS | Green | Baseline | CCS | Green |
| Demand (+5%) | -0,47% | u.f | 1,14% | -3,56% | u.f | -3,56% | -5,12% | u.f | -5,12% |
| Reference cost ($) | 8,59 | 9,18 | 9,67 | 14,31 | 17,22 | 14,31 | 16,2 | 18,94 | 16,2 |
| Demand (-5%) | 1,05% | **-1,53%** | -1,55% | **3,77%** | -13,70% | 6,36% | 0,37% | -3,01% | 76,73% |
| Demand (-10%) | 2,68% | **-2,72%** | 0,31% | **8,11%** | -10,10% | 8,11% | 3,89% | 22,44% | 43,15% |

### 5.6.1 Sensitivity analysis for emission factors

As shown in Table 5.6, the results show the impact of emission factors on the solutions obtained. It indicates that an increase in emission factors could bring some positive effects in terms of total cost reduction. Indeed, an overestimation of emission factors is accompanied by a decrease in the implementation of carbon abatement projects in the two scenarios since the emission intensity measure is used in this case. If we consider the absolute reduction measure, which fixes the quantity of total emission to be reduced, the results will be more sensitive, and we can observe a high impact on the total cost.

Table 5.6 Sensitivity analysis for emission factors

| Scenario | Baseline | | CCS | | Green | |
|---|---|---|---|---|---|---|
| Parameters | Total cost M$ | Total emissions KT $CO_2$ | Total cost M$ | Total emissions KT $CO_2$ | Total cost M$ | Total emissions KT $CO_2$ |
| Reference | 127 671 | 184 415 | 141 329 | 124 502 | 139 271 | 128 099 |
| Emission Factors (+25%) | 127 671 | 227 307 | 133 911 | 159 115 | 139 271 | 156 916 |
| *cost /emissions variations ( %)* | 0% | 23% | -5% | 28% | *0%* | *22%* |
| *Absolute variation* | - | **42 892** | -7 418 | **34 613** | - | **28 817** |
| Emission Factors (+50%) | 127 671 | 270 660 | 133 901 | 189 208 | 139 271 | 185 992 |
| *cost /emissions variations ( %)* | **0%** | 47% | **-5%** | 52% | **0%** | 45% |
| *Absolute variation* | - | 86 245 | -7 428 | 64 706 | - | 57 893 |

## 5.7 Optimal carbon abatement decisions

The complexity associated with the oil sector supply chain leads to different types of risks that need to be accounted for when planning a supply chain network (Amor et Ghorbel, 2018). The most common risks focus on operational risk, including production, capacity, inventory, prices, and demand. This section analyzes the decision-making process under environmental risk at each sector of the supply chain. Figure 5.12 shows the results of optimization for different reduction targets. If the reduction objective is less than 32%, we found that the CCS is recommended for the next twenty years.

The figure shows the implementation plans given the different objectives. For instance, if only a 5% reduction is needed, we can only implement the CCS for well five located in (W5). At a 30% reduction, we need to activate CCS in all wells. For 31%, we should add the implantation at the refiner located in (R3). Suppose the environmental regulation obliges the sector to achieve a $CO_2$ reduction of more than 32% reduction (see Annex V, Table-A V-2). In that case, the strategy must change, and the petroleum sector should invest in renewable solar energy solutions (see Annex VI, Table-A VI-2). With the full deployment of solar energy in the different sectors, it is possible to achieve a 62% reduction. In summary, figure 5.12 shows different Marginal Abatement costs according to three scenarios in terms of environmental risk reduction.

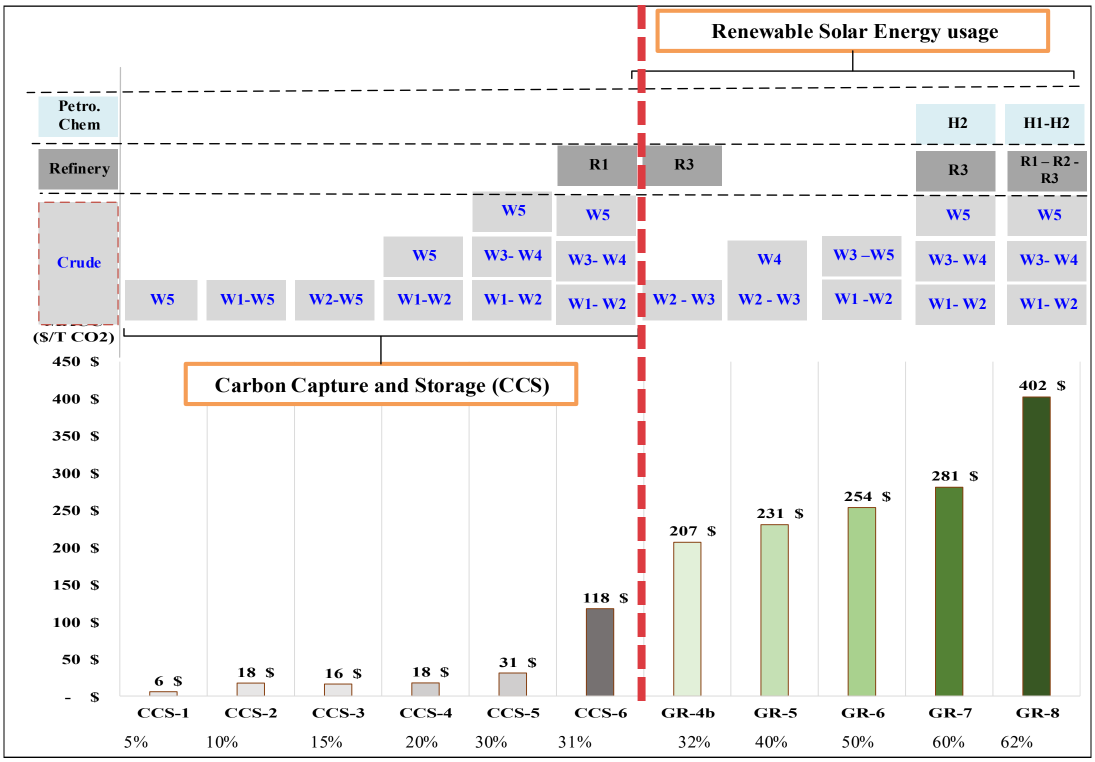



Figure 5.15 Optimal abatement potential under environmental risks

## 5.8 Implications

### 5.8.1 Theoretical implications

Implementing a green supply chain in the petroleum industry under the uncertainty of environmental regulations provides a better chance to produce a long-term eco-efficiency without an uncontrollable increase in petroleum products' cost. The most challenging problem is selecting the right technology and long-term investment decision-making considering the possible socio-economic ecosystem change and the increase in environmental costs. Therefore, the development of renewable and green energy and encouraging the usage of these technologies in the petroleum sector to reduce $CO_2$ emissions could be proposed by governmental policy to drive the transition toward greener petroleum products. If the regulation is more and more stringent, it will encourage the traditional supply chain to invest in these technologies and respect international agreements on climate change mitigation. According to Figure 14, choosing the appropriate technology for each sector and facility will guarantee cost control, ensure a highly competitive advantage, and help achieve the lowest marginal abatement cost.

### 5.8.2 Managerial implications

Managers can evaluate the performance of the petroleum supply chain by using the proposed method in this study. The findings indicated that the optimal joint usage of the current facilities with the proper selection of CCS projects and green technologies could improve the environmental performance with a minimum cost increase.  The proposed mathematical modeling framework provides decision-makers a suitable tool to evaluate different scenarios and help them take the right actions given the uncertainty in some specific parameters. Demand and emission factors for supply chain activities influence the decision-making process and the marginal abatement cost. Therefore, these factors should be estimated carefully to avoid errors in long-term decision-making.

### 5.8.3 Policy implications

Due to the low level of flexibility in the petroleum supply chain, a critical component to drive the transition to the green petroleum industry is the government subsidy (country level). The high voluntary investment in reducing carbon emission will attract new capital investment and create more jobs. The uncertainty in environmental laws will not help the sector establish the appropriate mitigation strategy and reduce the petroleum sectors' environmental burdens. Credible and stable pollution control regulations encourage proactive and more coordinated mitigation actions through the whole supply chain. The government must consider such regulations' impact to coordinate the upstream, midstream, and downstream efforts for cost-effective supply chain management solutions. The number of players involved in this process will reduce costs and encourage small players to contribute and be part of the global transition journey.

## 5.9 Conclusion

The problem as defined in this chapter is to address the green supply chain planning in the petroleum industry to investigate the impacts of sustainability implementation from a sector perspective. Also, the chapter examines the effects of incorporating investment decisions in different carbon emission reduction options and evaluating the supply chain performance based on the economic and environmental dimensions. To achieve that, we proposed a deterministic MILP model in order to minimize the crude, refinery, and petrochemical sectors' total cost and meet the environmental standards and regulations. This chapter mainly explores two major carbon abatement options, CCS and renewable energy, in the petroleum supply chain at the country level. This study proposes a MILP planning model that integrates economic and environmental to help decision-makers achieve sustainability objectives. The first objective function tries to minimize the total cost of the network, and the second one tries to mitigate $CO_2$ emission from the major activities in the supply chain. The model was tested for 20 years planning horizon in the Libyan petroleum sector.

The focus was on selecting the eco-efficient mitigation strategy given the economic uncertainty and the lack of stability in environmental regulations. Several numerical scenarios and sensitivity analyses were proposed to experiment with the model and evaluate the solution results. For this specific case, it has been shown that it's possible to achieve up to 32% carbon emission reduction if the carbon capture and storage projects are implemented in the different petroleum sectors. However, suppose the cumulative carbon reduction objective is more than 32 % for the next 20 years. In that case, it will be necessary to implement green (solar) energies to be used in the extraction, refineries, and petrochemical plants.

## CONCLUSION

Nowadays, due to the importance of sustainable supply chains and the challenges facing the petroleum sector, it has become a serious matter for the importance of the future generations in more detail. This research investigates the impacts of sustainability implementation on the petroleum supply chain from a sector perspective to address the sustainable issue in the petroleum sector. This research is different from previous studies. Most of the papers focus on sustainability in one or two levels, but our objective is to justify country-level sustainability in the petroleum supply chain. To achieve this purpose, the research objective is to identify the importance of sustainability implementation in the petroleum sector. So, this study aims to introduce the knowledge of the petroleum industry. Thereby, we defined the basic introduction to the readers to increase their understanding of the practices of this industry. Therefore, Chapter 1 provides a background about the petroleum industry with a full explanation of streams (crude, refinery, and petrochemical) from exploration processes, flows through different entities, transformation processes to the distribution activities.

Chapter 2 explores the comprehensive literature review and analysis of different papers to figure out critical gaps, opportunities, main features, and characteristics in the petroleum industry. Based on that, an extensive literature review was carried out to trace sustainable supply chain development. To achieve this aim, Chapter 2 carried out an SRL from a modeling perspective by discussing the selected papers according to the classification criteria to identify issues and problems. Also, establish or propose a taxonomy framework that includes the important component of the mathematical model (economic and environmental) in the petroleum sector to identify issues and concerns to provide direction for future research.

The third chapter proposed a generic MILP model in planning from an economic perspective at the sector level. It is an attempt to address a gap identified in the literature review. Also, it seeks to evaluate the performance in a deterministic economic setting. The goal of the optimization model is to helps the decision-makers to identify the production and distribution plan under some risky events. Furthermore, identify the decisions related to the flow between nodes, production capacities at each level, and how to satisfy the demand to maximize the profit from local and international markets. The model was tested on an existing case study petroleum sector in Libya to show the model's applicability in a real sector setting.

This study's fourth chapter applied the proposed tool (eco-efficient model) to establish the best strategy to decarbonize the petroleum supply chain under the uncertainty of environmental regulations. The model planning was implemented on a real case study to choose the best technology for minimizing $CO_2$ emissions while minimizing total cost. Also, the model was implemented with environmental constraints on emitted air emissions.

The fifth chapter of this study has provided the solution approach and numerical results of the eco-efficient model, including comparisons between three scenarios. The objective was to present the different carbon emission reduction options and evaluate supply chain performance based on the economic and environmental dimensions. Sensitivity analysis presented in some uncertain parameters to test the validity of the model. Also, to study the impact on the economy and environment. So, this section proposes a practical approach to managing the petroleum sector to handle the uncertainties to minimize the expected network total cost and identify the production and distribution plan under some risky events.

Thus, to ensure the movement toward sustainability, this study describes the solution procedure for the case study to represent the crucial sustainability implementation on the petroleum supply chain from a sector perspective to address the sustainable issue.

**Main contributions**

The main contribution of this thesis is how to develop a data-driven decision-making tool for eco-efficient supply chain planning in the petroleum sector at the country level. The network should consider all the petroleum sectors (crude, refinery, and petrochemical levels) of the petroleum supply chain, considering economic and environmental simultaneously. Also, the study integrates the long-term strategic decisions and mid-term tactical decisions in the model at once. So, we can summarize the mean contributions of this work represents in these points.

- All the sustainability models at the supply chain or company level do not focus on or tackle sustainability models at the country level.

The literature review indicates that most models focus on separate streams in the petroleum sector and cannot support strategic planning optimization from the country level. So, the characterizing literature review is required to identify the main component for the supply chain planning model and provides a conceptual framework on how to develop a decision model.

- Develop a data-driven decision-making tool for eco-efficient supply chain planning in the petroleum sector.

Propose a Mathematical model that integrate all sectors (country level) for eco-efficient. Because the privies models could not help the decision-makers, especially from the country's perspective, to develop a good strategy for next coming years integrates the long-term and mid-term decisions in the model at once.

- Apply the proposed tool with real data in order to establish the best strategy to decarbonize the supply chain in the petroleum sector under the uncertainty of environmental regulations. Also, the developed model is applied for the first time to a real case study in Libya to show the improved model application, visualize and validate the results from the optimization models.

**Limitations**

This study presents some limitations which could be subject to future research directions. First, the scope in the first step (SRL) was limited only to the modeling approach. Second, from a modeling perspective, the study in model 2 focuses only on $CO_2$ emission and does not consider other GHG emissions, especially in petroleum refineries. Also, the environmental evaluation did not consider other impacts such as groundwater contamination, waste streams, solid waste, and marine spills, especially during transportation. In addition, the study focuses only on two options (CCS and green) to mitigate $CO_2$ emissions and carbon abatement. Much more research needs to be done in future studies for considering other options for $CO_2$ reduction, such as cogeneration and energy efficiency.

Furthermore, the study used "intensity target" rather than "absolute target" to drive carbon emission reduction. Meeting an absolute target should be considered in another study. It will help the sector reduce carbon emission regardless of changes in the level of activities (demand variation) and the precision in emission factors. From a global sustainability perspective, the study does not include the social part since it was ignored in previous research, especially the quantitative approach.

Finally, sensitivity did not include other sources of uncertainty, such as product price fluctuations and disruptions events.

**Future work**

Even though important results have been studied along with this study and the discussion, there is still a lot of work to be done to identify and answer future research questions. Therefore, the suggestions for future work are counted as follows:

Future research could use this study to provide sustainable supply chain planning in the petroleum industry based on mathematical programming models. Moreover, our model can be used as a basis for further extensions by considering such as time-dependent demand and inventory constraints.

The sustainability of the petroleum supply chain is an important research area that gets more attention than it currently receives. Future work should include the social dimension as much as possible to evaluate the operation of the petroleum sector since supply chain activities significantly impact the social performance from a country-level perspective (job creation, safety, quality of life).

The petroleum companies in Libya should be aware of the significant environmental impact on its operations and the risk of the protection policies for different activities. Thus, more research needs to be done for developing appropriate technology for $CO_2$ reduction and continue to examine the actual implementation of the $CO_2$ reducing alternatives. Also, much more attention is needed, especially in the safety and protection of the environment, to avoid a significant crisis.

Research effort should be extended to provide real data about costs, specification of crude oil available in the market, cost of different fuel required for furnaces, cost of reduction technologies available for each air pollutant would generate more realistic and accurate results that can be trusted. These real data would reduce the number of assumptions needed in such a comprehensive model.

# ANNEX I

## PARAMETERS FOR MODEL IN CHAPTER 4

**Crude oil parameters**

$LC_{w}^{C}$ = Setup cost (Fixed cost) of location well $w \in W$ ($)

$Cap_{wt}^{C}$ = capacity in the well (bbl/y)

$Cap_{wt}^{C} - Min$ = Minimum Capacity in the well (bbl/y)

$EXC_{pwgt}^{C}$ = Variable extraction cost of $p \in P$ at wells $w \in W$ by using technology $g \in G$ during period $t \in T$ ($/bbl)

$PRC_{pwit}^{C}$ =Transportation cost of $p \in P$ transported from well $w \in W$ to storage tanks $i \in I$ at period $t \in T$ ($/bbl)

$PMC_{pijt}^{C}$ **:** Transportation cost of $p \in P$ transported from storage tanks $i \in I$ to market $j \in J$ at period $t \in T$ ($/bbl)

$PRR_{pwrt}^{C}$: Transportation cost of $p \in P$ transported from well $w \in W$ to to refinery $r \in R$ at period $t \in T$ ($/bbl)

$CSC_{pit}^{C}$ = Inventory cost of $p \in P$ at storage tanks $i \in I$ during period $t \in T$ ($/bbl)

$FCC_{pjt}^{C}$ = Selling price of crude oil $p \in P$ to market $j \in J$ at period $t \in T$ ($/bbl)

$DC_{pjt}^{C}$ = Demand of crude oil product $p \in P$ by crude market $j \in J$ at period $t \in T$ (bbl/y)

$SC_{pi}^{\max}$ = Overall storage capacity for product $p \in P$ at storage tanks $i \in I$ (bbl/y)

$VC_{t}^{\max,\min}$ = Maximum and Minimum production level of crude production at period $t \in T$ (bbl/y)

$CGW_{wgt}^{C}$ = Cost of technology $g \in G$ at Wells $w \in W$ at the period $t \in T$ ($)

$EFC_{pwg}^{C}$ =Emission factor associated with extracting $p \in P$ with technology $g \in G$ at wells $w \in W$ (kg $CO_2$/bbl)

$EFLC_{1}^{C}$ =Emission factor using pipeline transportation crude products to storage tanks and refinery (Kg $CO_2$/bbl·km)

$EFSC_{1}^{C}$ =Emission factor using ship transportation for crude products from storage tanks to market and petrochemical products to market (Kg $CO_2$/bbl·km)

**Refinery Parameters**

$LR_r^R$ = Setup cost (fixed cost) of refinery location $r \in R$ (\$)

$Cap_{rt}^R$ = capacity in the refinery (bbl/y)

$\gamma_{rep}^R$ = Yield of refinery product produced from processing crude product

$FRR_{est}^R$ = Selling price of $e \in E$ to market $s \in S$ at the period $t \in T$ (\$/bbl)

$PRM_{erst}^R$ = Transportation cost $e \in E$ transported from $r \in R$ to market $s \in S$ at $t \in T$ , (\$/bbl)

$PRH_{erht}^R$ = Transportation cost of $e \in E$ from refinery $r \in R$ to $h \in H$ at period $t \in T$ (\$/bbl)

$DR_{est}^R$ =Demand of refinery product $e \in E$ by the market $s \in S$ at the period $t \in T$ (bbl/y)

$VTR_{erxt}^R$ =Variable transformation cost $e \in E$ at $r \in R$ using technology $x \in X$ at $t \in T$ (\$/bbl)

$CGR_{rxt}^R$ =Variable transformation cost at refinery $r \in R$ using technology $x \in X$ $t \in T$ (\$/bbl)

$EFR_{erx}^R$ = Emission factor for transformation $e \in E$ at $r \in R$ technology $x \in X$ (kg $CO_2$/bbl)

$EFLR_1^R$ =Emission factor pipeline from refinery to petrochemical plants (kg $CO_2$/bbl. km)

$EFTR_1^R$ =Emission factor truck form refinery to the local market (Kg $CO_2$/bbl·km)

**Petrochemical Parameters**

$LH_h^H$ = Setup cost of petrochemical plant location $h \in H$ (\$)

$Cap_{ht}^H$ = capacity in the petrochemical (bbl/y)

$Cap_{ht}^H - Min$ = Minimum capacity in the petrochemical (bbl/y)

$\gamma_{hen}^H$ = Yield of petrochemical products produced from processing refinery products

$CSH_{nkt}^H$ = Unit inventory cost of $n \in N$ at storage tank $k \in K$ during the period $t \in T$ (\$/bbl)

$DH_{nzt}^H$ = Demand of petrochemical product $n \in N$ by market $z \in Z$ at period $t \in T$ (bbl/y)

$FHH_{nzt}^H$ = Selling price of the product $n \in N$ to market $z \in Z$ at period $t \in T$ (\$/bbl)

$SH^{\max}$ = Overall storage capacity for storage tank $k \in K$ (bbl/y)

$VH_{nht}^{\max}, VH_{nht}^{\min}$ = Maximum & Minimum production level of petrochemical product $n \in N$ at petrochemical plants $h \in H$ at the period $t \in T$ (bbl/y)

$PHK_{nhkt}^H$ = Transportation cost of $n \in N$ transported from petrochemical $h \in H$ to storage tank $k \in K$ at the period $t \in T$ (\$/bbl)

$PKZ_{nkzt}^H$ = Transportation cost of $n \in N$ transported from storage tank $k \in K$ to market $z \in Z$ at the period $t \in T$ (\$/bbl)

$VTH_{nhqt}^H$ = Variable transformation cost of the product $n \in N$ at the petrochemical plant $h \in H$ using technology $q \in Q$ during the time $t \in T$ (\$/bbl)

$EFH_{nhq}^{H}$= Emission factor associated with transformation petrochemical products $n \in N$ with technology $q \in Q$ at petrochemical (kg $CO_2$/bbl)

$EFLH_{1}^{H}$ =Emission factor using pipeline transportation petrochemical products to storage tanks (Kg $CO_2$/bbl·km)

$EFSH_{1}^{H}$ =Emission factor using ship transportation for petrochemical products from storage tanks to market (Kg $CO_2$/bbl·km)

## ANNEX II

## EMISSION FACTORS FOR PLANTS

Table-A II-1 Emission factor for extraction

| **Well** | **Technology** | **t $CO_2$/MM bbl** |
|---|---|---|
| W1 | GC1(Baseline) | 12,000 |
| W1 | GC2 (Capture) | 7,000 |
| W1 | GC3 (Green) | 3,000 |
| W2 | GC1 (Baseline) | 12,000 |
| W2 | GC2 (Capture) | 8,000 |
| W2 | GC3 (Green) | 3,000 |
| W3 | GC1 (Baseline) | 13,000 |
| W3 | GC2 (Capture) | 7,000 |
| W3 | GC3 (Green) | 3,000 |
| W4 | GC1 (Baseline) | 13,000 |
| W4 | GC2 (Capture) | 7,750 |
| W4 | GC3 (Green) | 3,000 |
| W5 | GC1 (Baseline) | 14,000 |
| W5 | GC2 (Capture) | 7,500 |
| W5 | GC3 (Green) | 3,000 |

Table-A II-2 Emission factor for refinery

| **Refinery** | **Technology** | **t $CO_2$/MM bbl** |
|---|---|---|
| R1 | XC1(Baseline) | 12,000 |
| R1 | XC2 (Capture) | 7,000 |
| R1 | XC3 (Green) | 4,000 |
| R2 | XC1(Baseline) | 12,000 |
| R2 | XC2 (Capture) | 8,000 |
| R2 | XC3 (Green) | 4,000 |
| R3 | XC1(Baseline) | 13,000 |
| R3 | XC2 (Capture) | 7,000 |
| R3 | XC3 (Green) | 4,000 |
| R4 | XC1(Baseline) | 13,000 |
| R4 | XC2 (Capture) | 7,750 |
| R4 | XC3 (Green) | 4,000 |
| R5 | XC1(Baseline) | 14,000 |
| R5 | XC2 (Capture) | 7,500 |
| R5 | XC3 (Green) | 4,000 |

Table-A II-3 Emission factor for petrochemical

| Petrochemical | Technology | t CO2/MM bbl |
|---|---|---|
| H1 | QC1(Baseline) | 12,000 |
| H1 | QC2 (Capture) | 7,000 |
| H1 | QC3 (Green) | 5,000 |
| H2 | QC1(Baseline) | 12,000 |
| H2 | QC2 (Capture) | 8,000 |
| H2 | QC3 (Green) | 5,000 |

**ANNEX III**

## EMISSION FACTORS FOR TRANSPORTATION

Table- A III-1 Emission factors for transportation
Source (Abella et Bergerson, 2012)

| Modes of transportation | Cost $/bbl | Kg $CO_2$/MM bbl | t $CO_2$/MMbl-km |
|---|---|---|---|
| Truck | 1.9 | 0.008587 | 5.679 |
| Maritime | 0.75 | 0.004294 | 0.693 |
| Pipeline | 0.5 | 0.000554 | 0.416 |

# ANNEX IV

# BASELINE RESULTS

Table- A IV-1 Baseline scenario details

| Sector | Cost/ bbl ($) | Activities | Total cost (M $) | Total cost (%) | Total emissions (KT $CO_2$) | Total emissions (%) |
|---|---|---|---|---|---|---|
| **Crude oil** | 8.59 | Fixed for Wells | 2,243 | 1.76% | - | - |
| | | Fixed cost for technology | 36,850 | 28.86% | - | - |
| | | Extraction | 30,049 | 23.54% | 135,097 | 73.26% |
| | | Transportation from wells to tanks | 14,994 | 11.74% | 2,379 | 1.29% |
| | | Transportation from tanks to market | 6,861 | 5.37% | 7,724 | 4.19% |
| | | Transportation cost well to the refinery | 152 | 0.12% | 202 | 0.11% |
| | | Inventory at storage tanks | 397 | 0.31% | - | - |
| **Refinery** | 14.31 | Fixed for Refinery | 1,113 | 0.87% | - | - |
| | | Fixed cost for technology | 24,965 | 19.55% | - | - |
| | | Transformation | 7,560 | 5.92% | 34,507 | 18.71% |
| | | Transportation refinery petrochemical | 17 | 0.01% | 172 | 0.09% |
| | | Transportation refinery to market | 250 | 0.20% | 1,141 | 0.62% |
| **Petrochemical** | 16.20 | Fixed for Petrochemical | 75 | 0.06% | - | - |
| | | Fixed cost for technology | 1,220 | 0.96% | - | - |
| | | Transformation | 637 | 0.50% | 2,885 | 1.56% |
| | | Transportation petrochemical to tank | 2 | 0.00% | 51 | 0.03% |
| | | Transportation tank to market | 232 | 0.18% | 257 | 0.14% |
| | | Inventory at storage tanks | 54 | 0.04% | - | - |
| **Total** | | | **127,671** | **100%** | **184,415** | **100 %** |

# ANNEX V

# CARBON CAPTURE AND STORAGE RESULTS

Table-A V-1 CCS-7 scenario details

| Sector | Cost/ bbl | Activities | Total cost (M $) | Total cost (%) | Total emissions (KT $CO_2$) | Total emissions $CO_2$ % |
|---|---|---|---|---|---|---|
| **Crude oil** | | Fixed for Wells | 2,243 | 0.00% | - | - |
| | | Fixed cost for technology | 49,395 | 9.83% | - | - |
| | | Extraction | 23,735 | -4.95% | 81,207 | 29.22% |
| | | Transportation from wells to tanks | 14,988 | 0.00% | 1,412 | 0.52% |
| | | Transportation from tanks to market | 6,898 | 0.03% | 7,628 | 0.05% |
| | | Transportation cost well to the refinery | 246 | 0.07% | 327 | -0.07% |
| | 9.18 | Inventory at storage tanks | 405 | 0.01% | - | - |
| **Refinery** | | Fixed for Refinery | 1,113 | 0.00% | - | - |
| | | Fixed cost for technology | 34,110 | 7.16% | - | - |
| | | Transformation | 5,303 | -1.77% | 30,444 | 2.20% |
| | 17.22 | Transportation refinery petrochemical | 46 | 0.02% | 69 | 0.06% |
| | | Transportation refinery to market | 251 | 0.00% | 1,148 | 0.00% |
| **Petrochemical** | | Fixed for Petrochemical | 75 | 0.00% | - | - |
| | | Fixed cost for technology | 1,420 | 0.16% | - | - |
| | | Transformation | 782 | 0.11% | 1,999 | 0.48% |
| | | Transportation petrochemical to tank | 32 | 0.02% | 9 | 0.02% |
| | 18.94 | Transportation tank to market | 233 | 0.00% | 258 | -0.001% |
| | | Inventory at storage tanks | 54 | 0.00% | - | - |
| **Total** | **45.34** | | **141,329** | **10.7 %** | **184,415** | **32.49 %** |

Table-A V-2 CCS scenario analysis

| CCS | | | | | | |
|---|---|---|---|---|---|---|
| **Scenarios** | **$CO_2$ Reduction target (%)** | **Total cost (M $)** | **Total emissions (KT $CO_2$)** | **Crude** | **Refinery** | **Petrochemical** |
| **Baseline** | 0% | 127 671 | 184 415 | - | - | - |
| **CCS-1** | 5% | 127 753 | 170 314 | W5 | - | - |
| **CCS-2** | 10% | 128 028 | 164 074 | W1, W5 | - | - |
| **CCS-3** | 15% | 128 173 | 153 177 | W2, W5 | - | - |
| **CCS-4** | 20% | 128 488 | 138 335 | W1, W2, W5 | - | - |
| **CCS-5** | 30% | 129 231 | 133 925 | W1, W2, W3, W4, W5 | - | - |
| **CCS-6** | 31% | 134 377 | 127 385 | W1, W2, W3, W4, W5 | R3 | - |
| **CCS-7** | 32% | 141 328 | 124 502 | W1, W2, W3, W4, W5 | R1, R2, R3 | H1, H2 |
| **CCS-8** | 33% | Unfeasible | | | | |

# ANNEX VI

# GREEN ENREGY DETAILS

## Table-A VI-1 Green energy (GR-8) scenario details

| Sector | Cost/ bbl | Activities | Cost M $ | Cost % | Emissions KT $CO_2$ | $CO_2$ % |
|---|---|---|---|---|---|---|
| **Crude oil** | 11.38 | Fixed for Wells | 2,243 | 0.00% | - | - |
| | | Fixed cost for technology | 72,900 | 28.24% | - | - |
| | | Extraction | 23,762 | -4.95% | 31,985 | 56.91% |
| | | Transportation from wells to tanks | 14,969 | -0.01% | 1,215 | 0.24% |
| | | Transportation from tanks to market | 6,898 | 0.03% | 7,628 | 0.05% |
| | | Transportation cost well to refinery | 346 | 0.01% | 460 | -0.01% |
| | | Inventory at storage tanks | 406 | 0.01% | - | - |
| **Refinery** | 20.51 | Fixed for Refinery | 1,113 | 0.00% | - | - |
| | | Fixed cost for technology | 41,910 | 13.27% | - | - |
| | | Transformation | 5,303 | -1.77% | 26,541 | 3.62% |
| | | Transportation refinery petrochemical | 46 | 0.02% | 68 | 0.09% |
| | | Transportation refinery to market | 251 | 0.00% | 1,147 | 0.00% |
| **Petrochemical** | 26.05 | Fixed for Petrochemical | 75 | 0.00% | - | - |
| | | Fixed cost for technology | 2,420 | 0.94% | - | - |
| | | Transformation | 782 | 0.11% | 685 | 2.19% |
| | | Transportation petrochemical to tank | 32 | 0.00% | 9 | 0.00% |
| | | Transportation tank to market | 233 | 0.00% | 257 | 0.00% |
| | | Inventory at storage tanks | 54 | 0.00% | - | - |
| **Total** | **57.94** | | **173,744** | **35.91 %** | **69,900** | **62,09%** |

## Table-A VI-2 Green energy scenario details

| Green | | | | | | |
|---|---|---|---|---|---|---|
| **Scenarios** | **CO2 Reduction target (%)** | **Total cost (M $)** | **Total emissions (KT CO2)** | **Crude** | **Refinery** | **Petrochemical** |
| **GR-1** | 5% | 129 871 | 171 665 | W1 | - | - |
| **GR-2** | 10% | 130 889 | 164 699 | W3 | - | - |
| **GR-2a** | 15% | 133 073 | 155 549 | W1, W3 | - | - |
| **GR-3** | 20% | 136 071 | 143 482 | W2 | - | - |
| **GR-4** | 30% | 139 271 | 128 099 | **W2, W3** | - | - |
| **GR-4a** | 31% | 139 710 | 126 269 | W2, W3 | R4 | - |
| **GR-4b** | 32% | **140 089** | 124 439 | W2, W3 | R3 | - |
| **GR-5** | 40% | 145 298 | 107 944 | W2, W3, W4 | - | - |
| **GR-6** | 50% | 151 244 | 91 500 | W1, W2, W3, W5 | - | - |
| **GR-7** | 60% | 158 922 | 73 200 | W1, W2, W3, W4, W5 | R3 | H2 |
| **GR-8** | 62% | 173 744 | 69 900 | W1, W2, W3, W4, W5 | R1, R2, R3 | H1, H2 |
| **GR-9** | 63% | Unfeasible | | | | |

# ANNEX VII

## SENSITIVITY ANALYSIS FOR DEMAND

Table-A VII-1 Emission factors variation

| | **BaselinE** | | | | |
|---|---|---|---|---|---|
| | Cost/bbl ($) | | | | |
| **Parameters** | Crude (Baseline) | Refinery (Baseline) | PetroChem (Baseline) | Total cost M$ (baseline) | Total KT $CO_2$ (baseline) |
| **Reference** | 8.59 $ | 14.31 $ | 16.20 $ | 127671 | 184.415 |
| **Demand (+10%)** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** |
| ***cost /emissions variations ( %)*** | - | - | - | - | **-** |
| **Demand (+05%)** | 8.55 $ | 13.80 $ | 15.37 $ | 131,565 | 193,524 |
| ***cost /emissions variations ( %)*** | | | | | |
| **Demand (-10%)** | 8.82 $ | 15.47 $ | 16.83 $ | 120,574 | 164,562 |
| ***cost /emissions variations ( %)*** | | | | | |
| **Demand (- 05%)** | 8.68 $ | 14.85 $ | 16.26 $ | 120,574 | 164,562 |
| ***cost /emissions variations ( %)*** | **CCS (30% $CO_2$ reduction target )** | | | | |
| **Parameters** | Cost/bbl ($) | | | | |
| **Reference** | Crude CCS -7 | Refinery CCS -7 | PetroChem (CCS -7) | Total cost M$ ((CCS -7)) | Total KT $CO_2$ ((CCS -7)) |
| **Demand (+10%)** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** |
| ***cost /emissions variations ( %)*** | - | - | - | - | - |
| **Demand (+05%)** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** |
| ***cost /emissions variations ( %)*** | - | - | - | - | - |
| **Demand (-10%)** | 8.93 $ | 15.48 $ | 23.19 $ | 121,617 | 129,232 |
| ***cost /emissions variations ( %)*** | | | | | |
| **Demand (- 05%)** | 9.04 $ | 14.86 $ | 18.37 $ | 127,422 | 129,232 |
| ***cost /emissions variations ( %)*** | | | | | |
| | **Green (30 % $CO_2$ reduction target)** | | | | |
| | Cost/bbl | | | | |
| **Parameters** | Crude Green | Refinery Green | PetroChem (Green) | Total cost M$ (Green) | Total KT $CO_2$ (Green) |
| **Reference** | | | | | |
| **Demand (+10%)** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** | **Unfeasible** |
| ***cost /emissions variations ( %)*** | **-** | **-** | **-** | **-** | **-** |
| **Demand (+05%)** | 9.78 $ | 13.8 $ | 15.37 $ | 146,065 | 128,001 |
| ***cost /emissions variations ( %)*** | | | | | |
| **Demand (-10%)** | 9.7 $ | 15.47 $ | 23.19 $ | 128,974 | 124,095 |
| ***cost /emissions variations ( %)*** | | | | | |
| **Demand (- 05%)** | 9.52 $ | 15.22 $ | 28.63 $ | 134,371 | 128,099 |
| ***cost /emissions variations ( %)*** | | | | | |

# ANNEX VIII

## SENSITIVITY ANALYSIS FOR EMISSION FACTOR

Table-A VIII-1 Emission factors variation

| | **BaselinE** | | | | |
|---|---|---|---|---|---|
| | Cost/bbl ($) | | | | |
| **Parameters** | Crude (Baseline) | Refinery (Baseline) | PetroChem (Baseline) | Total cost M$ (baseline) | Total KT $CO_2$ |
| **Reference** | **8,59 $** | **14,31 $** | **16,20 $** | **127671** | **184 415** |
| **Emission Factors (+25%)** | 8,59 $ | 14,30 $ | 16,20 $ | 127 671 | 227 307 |
| ***cost /emissions variations ( %)*** | - | - | - | 0% | **23%** |
| **Emission Factors (+50%)** | 8,59 $ | 14,30 $ | 16,20 $ | 127 671 | 270 660 |
| ***cost /emissions variations ( %)*** | - | - | - | **0%** | **47%** |
| | **CCS (30% $CO_2$ reduction target )** | | | | |
| **Parameters** | Cost/bbl ($) | | | | |
| **Reference** | Crude CCS -7 | Refinery CCS -7 | PetroChem (CCS -7) | Total cost M$ ((CCS -7)) | Total KT $CO_2$ ((CCS -7)) |
| **Emission Factors (+25%)** | **9,18** | **17,22** | **18,94** | **141329** | **124502** |
| ***cost /emissions variations ( %)*** | 9,17 $ | 14,30 $ | 16,21 $ | 133 911 | 159 115 |
| **Emission Factors (+50%)** | - | - | - | **-5%** | **28%** |
| ***cost /emissions variations ( %)*** | 9,17 $ | 14,31 $ | 16,20 $ | 133 901 | 189 208 |
| ***cost /emissions variations ( %)*** | - | - | - | **-5%** | 52% |
| | **Green (30 % $CO_2$ reduction target)** | | | | |
| | Cost/bbl | | | | |
| **Parameters** | Crude Green | Refinery Green | PetroChem (Green ) | Total cost M$ (Green) | Total KT $CO_2$ (Green) |
| **Reference** | **9,67** | **14,31** | **16,2** | **139271** | **128099** |
| **Emission Factors (+25%)** | 9,67 $ | 14,31 $ | 16,20 $ | 139 271 | **156 916** |
| ***cost /emissions variations ( %)*** | - | - | - | ***0%*** | ***22%*** |
| **Emission Factors (+50%)** | 9,67 $ | 14,31 $ | 16,20 $ | 139 271 | **185 992** |
| ***cost /emissions variations ( %)*** | - | - | - | **0%** | **45%** |

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