Green energy option for carbon abatement in the petroleum sector: an Optimization Based-Approach

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Abstract. This paper mainly explores a major carbon abatement for renewable energy, in the petroleum supply chain at the country level. Further, this study has provided the solution approach and numerical results of the eco-efficient model, including comparisons between two scenarios. Our primary objective was to present the carbon emission reduction options and evaluate supply chain performance based on the economic and environmental dimensions. Furthermore, the study examines the impact of incorporating investment decisions by minimizing the crude, refinery, and petrochemical sectors' total cost and meet environmental regulations. It presents a deterministic mathematical programming model for planning the supply chain. Furthermore, A novel mixed-integer linear programming model is presented in this study to evaluate the impact of introducing a stringent environmental regulation limiting greenhouse gas emissions. Experiments 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. This study shows that it is possible to reduce carbon emissions by up to 62% if the green (solar) energy projects are implemented in the different petroleum sectors.

Keywords: Green supply chain management, Sustainable supply chain, Planning, Multi-objective optimization, Petroleum supply chain, Carbon emissions.

1 Introduction

The petroleum industry is a significant part of the world economy, specifically in the energy sector. 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 [1]. The management of sustainability in the petroleum industry's complexity has grown significantly due to the high competition in a globalized market, the introduction of environmental regulations, and fluctuating demand and prices. Due to tremendous pressure, organizations must optimize their economic, environmental, and social performances when managing their supply chain to respect global regulation and prepare the transition towards a sustainable petroleum supply chain [2]. With the continuous development of technologies, more stringent standards are put forward for optimizing these complex supply chains. This increases the need for developing sustainable supply chain planning models that overcome these issues and achieve more integration between segments. Supply chain optimization models help supply chain Managers to make the right decisions across stages to generate a considerable profit and reduce environmental impact through an effective green supply chain [3]. In this regard, this study's key motivation comes from the solid global desire to reduce environmental effects such as air, water, and soil pollution. The Libyan country is one of the main producers of oil in the world. Libyan petroleum companies have widely ignored sustainability and environmental management [4]. A mixed-integer linear programming model and a multi-objective formulation are used to address this problem and provide decision-makers with a comprehensive strategic supply chain-planning tool to evaluate green supply options.

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 greening in the petroleum sector in Libya (government). Second, the model presents 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.

The rest of the paper was organized as follows. The relevant literature related to strategic/tactical sustainable (green) supply chain planning in the petroleum sectors was discussed in Section 2. Motivation and detailed problem description were provided in Section 3. Model development and solution method were given in Section 4. Comprehensive analysis and a brief conclusion are made in Section 5.

2 Literature review

Academics and practitioners consider the opportunities offered by decision-making tools for planning sustainable supply chain management in modern industries and organizations. In this section, the literature review aims to analyze the published papers that focus on sustainability in the petroleum industry and tackle the problem from a supply chain perspective (planning models with sustainability aspects). The objective is to characterize the decisions that we need to consider at the country level, the environmental problem that the papers discuss, modeling issues, and research methods used in each sector. Carbon emission reduction can be achieved using different options. These include incorporating carbon abatement objectives during the investment phase (cogeneration, carbon capture and storage, green technologies, renewable energy development) or improved supply chain planning [2].

A mixed-integer linear programming model (MILP) was considered by [5] to reduce the CO_2 emissions in the refinery sector to evaluate different technologies’ operational costs. The model considers crude distillation units (CDU). The results show a slight decrease in profit [6]. Developed a mixed-integer non-linear programming model (MINLP) to support the refinery in selecting the optimal CO_2 reduction strategies. The results show that up to a 30% reduction of CO_2 can be achieved if CCS is implemented. In the offshore petroleum fields,[7] developed the MILP model to study the different CO_2 mitigation technology for the offshore sector. The units were implemented and compared based on economic and environmental performance indicators. More recently, [8] formulated a tactical planning model by discussing environmental impact. The results showed that the proposed model could support the decision-maker to compromise between many production plans. Several technologies can significantly reduce the amount of CO_2 released and make our network more efficient and competitive.

In summary, the literature review indicates that few studies have been carried out to demonstrate how to achieve a sustainable supply chain in the petroleum industry domain. Therefore, it is essential to adopt an integrated approach where crude extraction, refinery, and petrochemicals activities are integrated into the same model to tackle the problem and coordinate the efforts to achieve a greener petroleum supply chain. As a result, this work's main contributions are that the first study includes the various sectors (crude, refinery, petrochemical, and transportation). Finally, this is the first study considering the Libyan country to analyze the CO_2 abatement mechanism utilizing a supply chain optimization perspective.

3 Problem Statement and Assumptions

3.1 Problem definition

This study is motivated by a real problem faced in Libya; Figure 1 illustrates the proposed model's processing stages for the Libyan petroleum supply chain at different levels. Indeed, Libya has 27 giant oil production fields. Further, more than 80% of the crude oil is exported to the international markets (European Union, Asia, and North America). Therefore, the Libyan government needs to implement emissions reduction strategies to reduce greenhouse gas (GHG) emissions, mainly CO_2. The Libyan petroleum sector emissions have increased from 52.2 Mt CO2 in 2010 to 57.9 Mt CO_2 in 2017 [10]. 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 with respect to the OPEC quota.

3.2 Assumptions

This study defines the total supply chain cost as an objective to minimize. We observed that CO_2 emissions are mainly used to evaluate the supply chain's environmental performance. Therefore, we include direct emissions from the following activities: extraction, production, refining, petrochemical, and transportation.

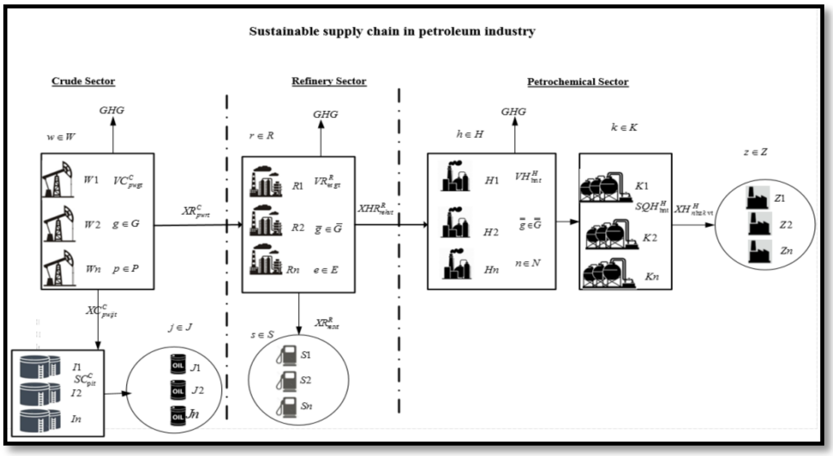


Fig. 1. The network of the petroleum supply chain sector

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, we consider the planning horizon for 20 years. It is divided into different periods in one year $t \in T$. Several assumptions are presented. We assume that the technologies are selected for crude extraction based on the oil field characteristics and geographical conditions to increase efficiency and reduce carbon emissions. The downstream must meet the market demands for various products with CO_2 emissions reduction targets. This growth in the petroleum sector can attract many investments, which requires a unique strategical plan to comprise the demand and supply [9]. 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) [10]. For this matter, refineries and petrochemical need to make more effort for new investment decision in technology selection at each level (crude, refinery, and petrochemical) to reduce CO_2 emissions. Finally, we assume that new environmental legislation is introduced to create a transition toward a more sustainable petroleum sector [11].

4 Mathematical Model

4.1 Model elements

This study defines the total supply chain cost as an objective to minimize. Based on the literature review, we observed that CO_2 emissions are mostly used to evaluate the supply chain's environmental performance. 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 Z^C during their operation. Also, transportation and distribution activities that generate emissions Z^R 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, operation, and variable costs). 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 equals 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, see the impact of technology change on the future, and transform the whole sector towards a greener petroleum supply chain.

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 $p \in P$ s 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). Let define BW^C_{wt} as a binary decision variable that takes a value of 1 if the well $w \in W$ at period is used in 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 sector parameters used in the model formulation is presented in Appendix.

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 Appendix.

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). $XHM^{H}_{nkz\,t}$ = 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. A summary of the petrochemical parameters used to formulate the model is presented in Appendix.

4.2 Model formulation

Economic performance

The deterministic model's objective function is to minimize the total cost, including (production, transportation, and storage cost) during the planning period. The economic performance 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

$$\text{Min}\, Z = Z^C + Z^R + Z^H \tag{1}$$

Z^C represents the fixed Installation cost of well, fixed cost technology, extraction cost of crude oil, transportation cost of crude oil from wells to storage tanks, transportation cost of crude oil from storage tanks to markets, transportation cost of crude oil from well to refinery), and inventory cost of crude oil at storage tanks.

$$\begin{aligned} Z^C = &\sum_{w,t} LC^C_{w}.BW^C_{w\,t} + \sum_{w,g,t} CGW^C_{wgt}.BWG^C_{wgt} + \sum_{w,g,t,p} EXC^C_{pwg\,t}.VC^C_{pwgt} + \sum_{p,w,g,t} BRC^C_{pwi\,t}.VC^C_{pwgt} \\ &+ \sum_{p,i,j,t} PMC^C_{pijt}.XCM^C_{pijt} + \sum_{p,w,r,t} PRR^C_{pwrt}.XR^C_{pwrt} + \sum_{p,i,t} CSC^C_{pit}.SC^C_{pit} \end{aligned} \tag{2}$$

Z^R represents the fixed Installation cost of the refinery, fixed cost of refinery technology, transformation cost of refinery, transportation cost of refinery products from refinery to petrochemical plants, and transportation cost of refinery products from refinery to market.

$$\begin{aligned} Z^R = &\sum_{r,t} LR^R_{r}.BR^R_{rt} + \sum_{r,x,t} CGR^R_{rxt}.BRG^R_{rxt} + \sum_{e,r,x,t} VTR^R_{erxt}.VR^R_{erxt} + \\ &\sum_{e,r,h,t} XRH^R_{erht}.PRH^R_{erht} + \sum_{e,r,s,t} XRM^R_{erst}.PRM^R_{erst} \end{aligned} \tag{3}$$

Z^H represents the fixed Installation cost of petrochemical plants, fixed cost to petrochemical technology, transformation cost of petrochemical plants, transportation cost of petrochemical products from to petrochemical to the storage tank, and transportation cost of petrochemical products from the storage tank to market.

$$\begin{aligned} Z^H = &\sum_{h,t} BH^H_{ht}.LH^H_{h} + \sum_{h,g,t} BHG^H_{hqt}.CGH^H_{hqt} + \sum_{n,h,g,t} VH^H_{nhqt}.VTH^H_{nhqt} + \\ &\sum_{n,k,t} SH^H_{nkt}.CSH^H_{nkt} + \sum_{n.h.k.t} XH^H_{nhkt}.BHK^H_{nhkt} + \sum_{n,k,z,t} XHM^H_{nkzt}.BKZ^H_{nkzt} \end{aligned} \tag{4}$$

Environmental performance

The major environmental sustainability issues are; GHG emission, toxic and hazardous wastes, oil spills, and water pollution [12] [13] [4]. However, each of these challenges creates many 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 6, which evaluates CO_2 emissions from crude oil, refining, and petrochemical sectors.

$$\text{Min } E = \text{Min } E = E^C + E^R + E^H \tag{6}$$

E^C calculates the emission associated with oil extracting activities

$$E^C = \sum_{p,w,g,t} EFC^C_{pwg} VC^C_{pwgt} + \sum_{p,w,i,t} EFLC^C_1 XC^C_{pwit} + \sum_{p,w,r,t} EFLC^C_2 .XR^C_{pwrt} + \sum_{p,i,j,t} EFSC^C_1 .XCM^C_{pijt} \tag{7}$$

E^R calculates the emission associated with transformation refinery activities

$$E^R = \sum_{e,r,x,t} EFR^C_{erx} .VR^R_{erxt} + \sum_{e,r,h,t} EFLR^R_1 .XRH^R_{erht} + \sum_{e,r,s,t} EFTR^R_1 .XRM^R_{erst} \tag{8}$$

E^H calculates the emission associated with transformation petrochemical activities.

$$E^H = \sum_{n,h,q,t} EFH^H_{nhq} .VH^H_{nhqt} + \sum_{n,h,k,t} EFLH^H_1 .XH^R_{nhkt} + \sum_{n,k,z,t} EFSH^H_1 .XHM^H_{nkzt} \tag{9}$$

Crude oil sector constraints

Crude oil demand satisfaction

$$\sum_i XCM^C_{pijt} = DC^C_{pjt} \qquad \forall p \in P, \forall j \in J, \forall t \in T \tag{10}$$

Inventory balance of crude oil at storage tanks

$$SC^C_{pit} = SC^C_{pit-1} + \sum_w XC^C_{pwit} - \sum_j XCM^C_{pijt} \qquad \forall p \in P, \forall i \in I, \forall T > 1 \tag{11}$$

Crude oil production constraints

$$\sum_g VC^C_{pwgt} = \sum_i XC^C_{pwit} + \sum_r XR^C_{pwrt} \qquad \forall p \in P, \forall w \in W, \forall t \in T \tag{12}$$

Refinery sector constraints

Refinery demand satisfaction

$$DR^R_{est} = \sum_r XRM^R_{rest} \qquad \forall e \in E, \forall s \in S, \forall t \in T \tag{13}$$

Petrochemical sector constraints

Petrochemical demand satisfaction

$$\sum_k XHM^H_{nkzt} = DH^H_{nzt} \qquad \forall n \in N, \forall z \in Z, \forall t \in T \tag{14}$$

Inventory balance of petrochemical at tanks for period 1

$$SH^h_{nk1} = \sum_h XH^H_{nhk1} - \sum_z XHM^H_{nkz1} \qquad \forall n \in N, \forall k \in K \tag{15}$$

Petrochemicals production constraints

$$\sum_q VH^H_{nhqt} \geq \sum_k XH^H_{nhkt} \qquad \forall n \in N, \forall h \in H, \forall t \in T \tag{16}$$

4.3 Solution method

The ε-constraint method is considered a solution procedure in this paper because the decision-maker does not need to articulate a prior preference for the objective. Thus, one objective is selected for optimization. The remaining objectives are reformulated as constraints[11]. The objective, Z, is selected for the optimization to solve the previously formulated model (sub-section 3.4) using the ε-constraint method.

5 Experimentation and results

This section describes the solution procedure and numerical results for the case study. 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).

5.1 Baseline scenario

Most of the data has been collected from the Libyan National Oil Corporation (NOC) collaboration at different levels. Other data were estimated using official websites, published reports, and some previous studies[14],[15], [16-18]. In this study, we consider only the direct emissions from certain activities in each sector. To experiment with the proposed model, two scenarios have been developed. The first scenario (Baseline) is when we optimize the petroleum supply chain without considering the CO_2 reduction objective. 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 1 and compare costs and the CO_2 emissions contributions of the different oil sectors.

Table 1. Baseline scenario of different sectors

Sector	Total cost (M $)	Total cost (%)	CO_2 Emissions (KT CO_2)	Total CO_2 emissions (%)
Crude oil	69,539	54	135,096	73
Refinery	33,638	26	34,506	19
Petrochemical	1,986	2	2,885	2
Transportation	22,509	18	11,927	6
Total (20 years)	127,672	100	184,415	100
Average	6,384 (M$/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). Production of crude oil in upstream operations accounts for the highest emissions because of the energy-intensive production methods to extract crude oil, especially in offshore platforms. Also, the refinery sector is massively emitting CO_2 because of the complex process systems that synthesize many products while utilizing large amounts of energy and hydrogen for hydrotreatment processes.

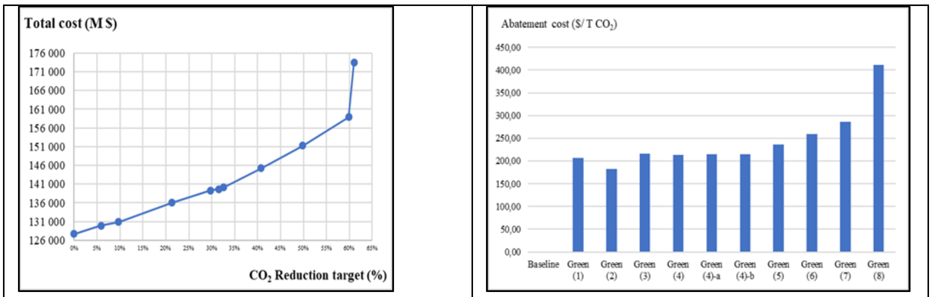
5.2 Green energy scenario

For the second scenario, we consider investing in renewable solar energy for extraction and production activities in refinery and petrochemical plants. Table 2 shows the results with the details on emissions reduction by implementing green (solar) technologies. We can observe that the supply chain cost increased for this scenario compared to the Baseline. For instance, with a 62% CO2 emissions reduction objective (scenario GR-7), the total cost increases by 36.11% and brings the total cost to173,744 M$.

Table 2. Green energy scenario of different CO_2 reduction versus Baseline

Scenario	CO_2 Reduction (%)	Cost Increase (%)	CO_2 decrease (%)	Crude ($/bbl)	Refinery ($/bbl)	Petrochemical ($/bbl)
Baseline	0	0	0	8.59	14.31	16.20
GR-1	10	2.52	10.69 %	8.89	14.31	16.20
GR-2	20	6.58	22.2%	9.37	14.31	16.20
GR-4	30	9.09	30.54 %	10.24	14.31	16.21
GR-5	40	13.81	41.47 %	10.8	14.38	16.22
GR-6	50	18.46	50.38 %	11.38	14.66	16.21
GR-7	62	36.11	60.31 %	11.38	20.51	26.05
GR-8	63	Unfeasible				

It indicates that this option can help the petroleum industry in Libya achieve up to a 62% reduction of CO_2 emissions (Green-7- scenario), which increases the total cost by 35.91%, which is in line with similar studies in the literature [19-21]. Also, the Pareto frontier in Figure 2 (a) demonstrates the set of Pareto optimal solutions (those that are not dominated by any other feasible solutions). Also, Figure 2 (b) determines the marginal abatement costs for different CO_2 reduction target scenarios. Simultaneously, we observe a reduction in the extraction and transformation costs resulting from more efficiency in the extraction of crude and the refinery transformation. By far, using Green- 7- scenario we will not reduce more than 62 % [19-21].



a) Pareto frontier   b) Abatement costs

Fig.2. Total and abatement costs for CCS scenarios

Figure 3 presents the comparison cost and CO_2 perspective between the baseline and Green 7 (GR-7) scenarios, which generate a 61.47% reduction in CO_2, but a cost increase to 35.91%. To achieve the abatement objective, it needs significant investment in the crude (upstream) and refinery sectors (midstream).

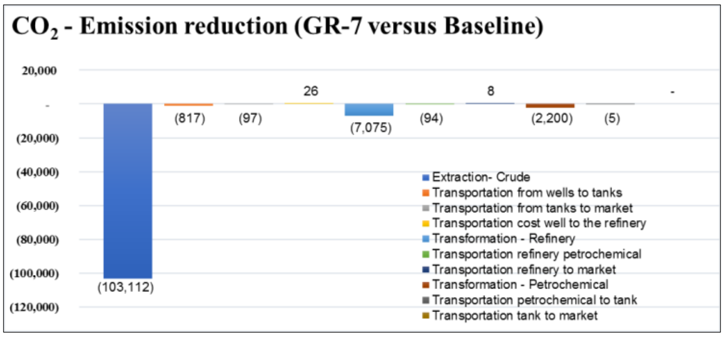
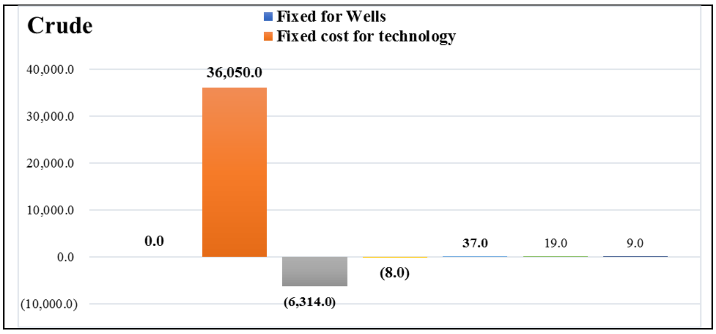


Fig. 3. Comparison between Baseline & GR-7 scenarios

Figure 4 compares cost and CO_2 perspectives between the baseline and GR-8 scenarios in different sectors for each sector.



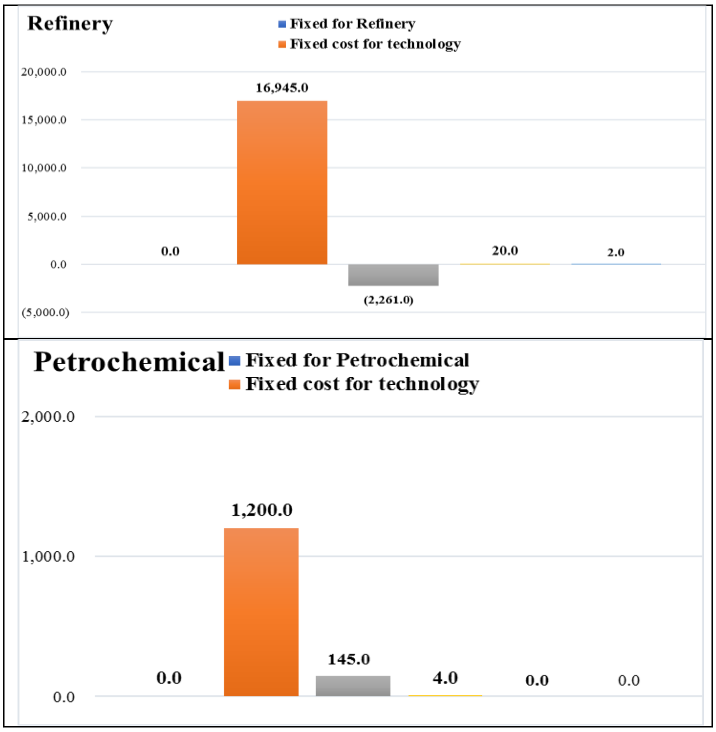


Figure. 4. Comparison between the GR-8 and Baseline scenarios in different sectors

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.

6 Conclusion

This paper mainly explores a major carbon abatement for renewable energy, in the petroleum supply chain at the country level. Further, this study has provided the solution approach and numerical results of the eco-efficient model, including comparisons between two scenarios. The objective was to present the different carbon emission reduction options and evaluate supply chain performance based on the economic and environmental dimension. In this case, it will be necessary to implement green (solar) energies to be used in the extraction, refineries, and petrochemical plants. Although this study focuses on the Libyan country as a case example, the same methodology can be applied to other countries to evaluate the petroleum sector's carbon abatement options at the country level. In this case, the mathematical model could be adjusted and take into account additional country-specific constraints. For the limitations, much more research needs to be done in future studies for considering other options for CO_2 reduction. Finally, research efforts should be extended to study different methodologies to deal with air, land, and sea pollutants and other sources of uncertainty, such as product prices, resource availability, and disruptions events

Appendix

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 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)

γ_{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^{R}_{erx} = Emission factor for transformation $e \in E$ at $r \in R$ technology $x \in X$ (kg CO_2/bbl)
$EFLR^{R}_{1}$ =Emission factor pipeline from refinery to petrochemical plants (kg CO_2/bbl. km)
$EFTR^{R}_{1}$ =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^{H}_{ht} = capacity in the petrochemical (bbl/y)
$Cap^{H}_{ht} - Min$ = Minimum capacity in the petrochemical (bbl/y)
γ^{H}_{hen} = Yield of petrochemical products produced from processing refinery products
CSH^{H}_{nkt} = Unit inventory cost of $n \in N$ at storage tank $k \in K$ during the period $t \in T$ ($/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} = 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)
$VH^{\max}_{nht}, VH^{\min}_{nht}$ = 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^{H}_{nhkt} = 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^{H}_{nkzt} = 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^{H}_{nhqt} = 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^{H}_{nhq} = Emission factor associated with transformation petrochemical products $n \in N$ with technology $q \in Q$ at petrochemical (kg CO_2/bbl)
$EFLH^{H}_{1}$ =Emission factor using pipeline transportation petrochemical products to storage tanks (Kg CO_2/bbl·km)
$EFSH^{H}_{1}$ =Emission factor using ship transportation for petrochemical products from storage tanks to market (Kg CO_2/bbl·km)

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