

# Key Factors Governing the Carbon Footprint of Operational Activities at Khalda Petroleum Company

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## Abstract

As concerns about climate change and carbon emissions continue to rise, many companies and organizations are eager to assess their “carbon footprint” to understand their impact on this global challenge. In the realm of oil production, the environmental consequences can be quite serious, leading to issues like air pollution and heightened global warming potential (GWP) due to increased greenhouse gases (GHG). This study investigates the greenhouse gas (GHG) emissions associated with crude oil and natural gas production at Khalda Petroleum’s sites in Egypt’s western desert. Activities contributing to emissions were categorized by operational boundaries—Scopes 1, 2, and 3—and their carbon footprints were quantified. Key emission sources were identified, with gas flaring and diesel consumption emerging as major contributors, while water supply and refrigerants had minimal impact. Linear relationships revealed strong positive correlations between fuel use, flaring, and venting activities, and GHG emissions, with  $R^2$  values close to 1. Polynomial relationships highlighted the influence of device efficiency on emissions, suggesting that optimizing combustion and refrigerant systems is critical for reduction. Recommendations include adopting advanced flaring technologies, switching to cleaner fuels, enhancing equipment efficiency, and integrating renewable energy sources. These strategies aim to minimize emissions while maintaining operational efficiency, aligning Khalda Petroleum with global sustainability standards. Continuous monitoring, employee training, and stakeholder collaboration are emphasized as essential components for long-term success.

## Keywords

Climate Change, Potential Global Warming, Petroleum Production, GHG

## 1. Introduction

The rising concerns over climate change and environmental degradation have brought intense focus on the carbon footprint of industrial sectors, particularly petroleum production. As a significant contributor to greenhouse gas emissions, the petroleum industry faces increasing pressure to mitigate its environmental impact, especially in the operational phases that contribute substantially to carbon emissions.

The factors that influence the carbon footprint in oil production are quite complex and involve a blend of technology, operational processes, and regulations. It's not just black and white; some of these elements can actually play a positive role by reducing greenhouse gas emissions, while others might simply contribute to global warming without us even realizing it. So, it's a bit of a mixed bag when it comes to understanding how our oil production impacts the environment.

### 1.1. Objectives

Understanding these factors and how they relate to greenhouse gas emissions is crucial if we want to develop effective strategies for reducing those emissions and achieving our global sustainability goals. This paper explores the key elements that impact the carbon footprint associated with daily operations in petroleum production. We're looking at energy consumption trends, equipment efficiency, and compliance with regulations. By examining these components, the research aims to provide practical suggestions for lowering carbon emissions and enhancing our environmental responsibility in the petroleum industry.

Khalda Petroleum Production Company was selected as a case study to represent other companies in the industry. We took a close look at all its operational data and analyzed it thoroughly. We'll be keeping track of the greenhouse gas (GHG) emissions from KPC's activities and calculating its carbon footprint step by step. This will be done following the standards and methods that meet the approval of the Intergovernmental Panel on Climate Change (IPCC) and other reputable organizations, including the American Environmental Protection Agency (EPA), the World Resources Institute's Corporate Greenhouse Gas Emissions Protocol, and the New Zealand Government's Emissions Measurement Guide for Organizations.

### 1.2. Previous Literatures

A lit review of previous studies and researches is basically a mix of all the existing research on a topic. It gives us the scoop on key findings, trends, and what's still missing in the knowledge bank. The goal is to paint a clear picture of where the field stands by looking at what scholars and researchers have done. It sets the stage

for the study, helping to shape the research question and showing why the topic matters in the bigger academic picture. Here's a quick look at some recent studies we'll explore next:

In Algeria, gas flaring happens a lot, which leads to higher carbon intensities in those fields. On the flip side, places like Norway, where regulations are tighter, manage to keep emissions down thanks to better methane management and less flaring ([The World Bank, 2022](#)). The Oil Production Greenhouse Gas Emissions Estimator (OPGEE) helps us figure out the greenhouse gas emissions for each barrel of oil. The results vary quite a bit, showing emissions anywhere from 10 to over 70 kg of CO<sub>2</sub>-equivalent. This difference really depends on the specific oil field and the extraction methods used. ([IEA & Stanford EAO Group, 2022](#)). [The International Energy Agency \(IEA\) \(2023\)](#) points out that by electrifying facilities with renewable energy, getting rid of non-emergency flaring, and using carbon capture technologies, which together could cut emissions from oil and gas production by over 50% by 2030 in a net-zero emissions scenario. [Charpentier et al. \(2009\)](#), examine emissions from oil sands, which represent a high carbon footprint in petroleum production. The magnitude of Canada's oil sands reserves, they're rapidly expanding and energy intensive production, combined with existing and upcoming greenhouse gas (GHG) emissions regulations motivate an evaluation of oil sands-derived fuel production from a life cycle perspective. [Brandt \(2011\)](#) explores the impact of oil depletion on the energetic efficiency of oil extraction and refining in California. These changes are measured using energy return ratios.

[Alvarez et al. \(2012\)](#) discuss methane leakage, which is a major contributor to GHG emissions in petroleum operations. They also illustrate the use of technology warming potentials as a robust and transparent way to compare the cumulative radiative forcing created by alternative technologies fueled by natural gas and oil or coal by using the best available estimates of greenhouse gas emissions from each fuel cycle. [The International Energy Agency \(2023\)](#) provides global data on GHG emissions from petroleum production and consumption through the World Energy Outlook and Global Methane Tracker. IPCC Guidelines for Greenhouse Gas Inventories (2006), has provided Guidelines for Greenhouse Gas Inventories, released back in 2006, laid out some pretty handy methods for figuring out how much emissions come from extracting and processing fossil fuels. It's like a roadmap for anyone looking to understand the impact of these activities on our environment. [Rubin et al. \(2004\)](#) address carbon reduction technologies, which are applicable to reducing emissions in oil and gas extraction. [Jaramillo et al. \(2009\)](#) compare greenhouse gas (GHG), SO<sub>x</sub>, and NO<sub>x</sub> life-cycle emissions of electricity generated with NG/LNG/SNG and coal. This life-cycle comparison of air emissions from different fuels can help us better understand the advantages and disadvantages of using coal versus globally sourced NG for electricity generation. [Davis and Socolow \(2014\)](#) provide insights into how policy can address emissions in energy-intensive industries like petroleum. [New Zealand Ministry for](#)

*Environment* (2022) has provided measuring emissions guide for organization. This guide supports organizations taking climate action. The guide aligns with and endorses the use of the *GHG Protocol Corporate Accounting and Reporting Standard* and ISO 14064-1: 2018. Zheng et al. (2023) estimated the GHG emissions from extractive activities globally with a focus on China, and assessed the main emission drivers. In addition, they predicted the Chinese extractive industry emissions in the context of global mineral demand and cycling. Russell (2016) laid out a method for figuring out and sharing emissions from fossil fuel reserves. He pointed out that knowing potential emissions is key for making smart choices. If companies tap into their fossil fuel reserves, we could blow past the carbon budget for keeping global warming under 2°C, leading to crazier weather, rising sea levels, and damaged infrastructure. The Paris Agreement pushes governments for net-zero emissions and aims to cap temperature rise at 2°C, with a goal of hitting 1.5°C. To hit these targets, we need to leave some fossil fuels untouched unless we get solid carbon capture tech. Fossil fuel companies and their stakeholders need this info to make informed decisions about emissions and reserves.

### 1.3. Problem Statement

The contribution of petroleum production operations to greenhouse gas (GHG) emissions is a significant issue in the global effort to mitigate climate change. Petroleum production activities, including extraction, processing, transportation, and refining, release large amounts of GHGs—primarily carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O)—into the atmosphere. These emissions result from combustion processes, fugitive emissions, flaring, and venting of gases, key challenges include:

**1) Extraction:** Emissions during oil extraction arise from energy-intensive processes and leaks. Methane, a potent greenhouse gas, is often unintentionally released due to equipment leaks, and venting practices are common in older facilities.

**2) Processing and Refining:** Refining crude oil into usable products is energy-intensive and involves burning fossil fuels. This process contributes significantly to CO<sub>2</sub> emissions due to the high energy demand for heating and distillation.

**3) Transportation and Distribution:** The movement of petroleum products via pipelines, tankers, and trucks generates GHG emissions, particularly CO<sub>2</sub>, from fuel combustion. Additionally, leaks and spills in pipelines can release methane into the atmosphere.

**4) End-use Products:** Although downstream of production, the ultimate combustion of petroleum-derived products (such as gasoline, diesel, and jet fuel) is one of the largest sources of GHG emissions.

Despite efforts to mitigate emissions, the petroleum industry remains one of the largest sources of anthropogenic GHG emissions worldwide. This poses challenges for meeting international climate goals, such as those outlined in the Paris Agreement, and exacerbates environmental degradation, including rising sea

levels, extreme weather events, and loss of biodiversity. Reducing the GHG emissions from petroleum production requires technological advancements, stringent regulatory frameworks, and a shift toward sustainable energy sources. Addressing this problem is crucial to achieving global emissions reduction targets and limiting global warming.

## 2. Methods and Techniques

### 2.1. Activity Data Collection

KPC has been running its operations for decades across twelve sites. All sites are equipped with around thirty-two combustion devices, including turbines, boilers, and heaters, which collectively consume about 4980 mmcf of natural gas per year as direct fossil fuel. Additionally, the company's fleet of vehicles—trucks and buses used for transporting materials, products, waste, and personnel—uses about 19,228,932 liters of diesel annually (around 5079748.8 gallons). Electric generators also play a role, consuming approximately 56,076,902 liters of diesel each year (about 14813957.3 gallons).

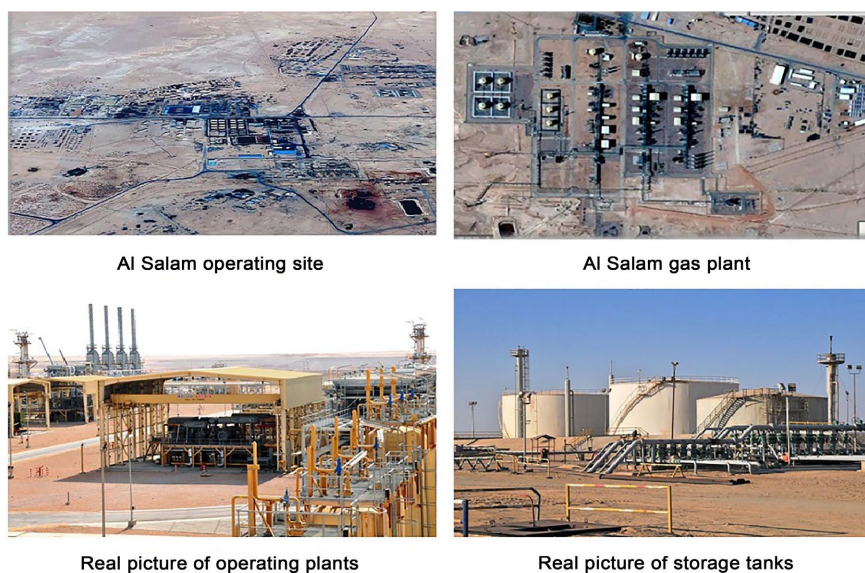
For drinking and sanitary needs, KPC receives around 5084.8 cubic meters of fresh water annually from Matrouh governorate via a national network, supplied by a specific contractor. On top of that, KPC operates 5500 medium and large refrigerators, along with various sizes of small air-conditions, commercial stand-alone chillers, which are filled with 2550.8 kilograms of different refrigerants like R22, R134A, R404A, R407A, and R110A. However, it's worth noting that any leaks from these units can contribute to global warming, with the total amount of leaked gas being around 201 kilograms

### 2.2. Data Certainty

All the previous activity data were gathered from reliable sources. The fuel consumption—whether it's natural gas or diesel—was measured using flow meters at the fuel supply stations. The water was delivered by a contractor who uses regular-sized tanks to bring it to Khalda Company from the national network in Matrouh governorate. When it comes to recharging the refrigerators with HFCs, maintenance officer use special devices that also have flow meters to ensure we're using the right amount of gas. So, it's really important that we have a solid understanding of where our activity data is coming from and how much of it the company has. We want to be super confident in that data and any uncertainties should naturally start to disappear. **Figure 1** maps of some operating sites and real pictures of some operating plant and storage tanks.

Calculating the carbon footprint of an organization, activity, or product involves measuring the greenhouse gas (GG) emissions associated with each stage of a process or supply chain. The goal is to quantify emissions from various sources and understand their impact. There are a bunch of methods used to measure and calculate carbon footprints, and there are also various techniques to recognize the relationships between specific activities and their emissions. In this

research paper the specific method used to calculate the carbon footprint tied to the production activities of KPC.



**Figure 1.** Google maps and photographic pictures for operation sites.

### 2.3. Carbon Accounting and Scope Analysis Methods

Her GHG emissions categorize related to operation boundaries (scope 1, scope 2, and scope 3) to analyze emissions based on their origin:

- **Scope 1:** Direct emissions from owned sources.
- **Scope 2:** Indirect emissions from purchased electricity.
- **Scope 3:** All other indirect emissions in the value chain.

By isolating emissions by scope, specific activities and their contributions can be tracked to the carbon footprint, from industrial processes (scope 1) to electricity consumption (scope 2) to emissions from suppliers or product usage (scope 3).

Here's **Table 1** that breaks down all the activities that release GHG emissions, where they come from, and which scope they fall into.

**Table 1.** The activities release GHG emission at Khalda Petroleum Company.

Activity Data	Operation Boundary	Combustion Devices /Utilities	Units	Fuel/ Resource	Consumed Quantities
Stationary fuel combustion	Scope 1	• Turbines /boilers/heaters	mmcf/y	NG	4980
		• Diesel Electricity Generators	Litter/y	Deisel	56,076,902
Mobile fuel combustions	Scope 1	• Trucks/vehicles/buses/cars	Litter/y	Deisel	19,228,932
Water supplies	Scope 3	• Drinking and sanitary utilities	M <sup>3</sup> /y	Water	5084.8
Air conditions and cooling	Scope 1	• Refrigerants	Kg/y	Gas	2550.8
Optimizing pressure	Scope 1	• Flare	m <sup>3</sup> /y	Gas	178,393,008
Venting from pipes and tanks	Scope 1	• Valves/pipes/joints/tanks		Crude Oil	3,178,794
				NG	3,681,406

To calculate carbon footprints, organizations and individuals can use a variety of methods. Key frameworks include the **GHG Protocol** and **ISO 14064-1**. The GHG Protocol, developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development. This protocol provides comprehensive guidelines, making it one of the most widely used frameworks for corporate carbon footprint reporting and reduction strategies. Meanwhile, ISO 14064-1 is an international standard that emphasizes quantifying and managing greenhouse gas emissions, making it particularly useful for organizations aiming to follow globally recognized sustainability practices. Compatible emission factors used to figure out the carbon footprint sourced from various issued and certified references as following.

- [Federal Register \(2010\)](#).
- [IPCC \(2006\)](#).
- [EIA \(2019\)](#).
- [EIA \(2021\)](#).
- [EPA \(2021\)](#).

Calculating the carbon footprint from flaring gases during oil production is all about figuring out the greenhouse gas (GHG) emissions involved. Here's a straightforward breakdown:

**Formula:** Carbon Footprint (CO<sub>2</sub>e) = Volume of Gas Flared × Emission Factor × Global Warming Potential

**Steps to Calculate:**

1) Measure the Gas Flared: Start by determining the volume of gas flared over a specific period, measured in standard cubic meters or cubic feet.

2) Analyze the Gas Composition: Look into what gases are present in the flared mix, such as methane, ethane, propane, and so on.

3) Calculate CO<sub>2</sub> Emissions: For each component of the gas, apply its emission factor using this formula: Emissions (kg) = Volume of Gas Component Flared × Emission Factor (kg-CO<sub>2</sub>/m<sup>3</sup>).

4) Account for Methane Emissions: If there's incomplete combustion, some methane could escape. A specific factor uses for that:

$$\text{Emissions (kg)} = \text{Volume of gas flared} \times \text{methan slippage factor} \quad (1)$$

5) Convert to CO<sub>2</sub>-equivalent: Multiply the methane emissions by its Global Warming Potential (GWP). For instance, CH<sub>4</sub> is roughly 25 - 28 times more potent than CO<sub>2</sub> over a century:

$$\text{CH}_4 \text{ emissions in CO}_2\text{e} = \text{CH}_4 \text{ emissions (kg)} \times \text{GWP} \quad (2)$$

6) Add It All Up: Finally, combine the CO<sub>2</sub> and CH<sub>4</sub> emissions (in CO<sub>2</sub>-equivalent) to get your total carbon footprint:

$$\text{Total emissions (CO}_2\text{e)} = \text{CO}_2 + \text{CH}_4 \text{ (in CO}_2\text{e)} \quad (3)$$

- CO<sub>2</sub> Emission Factor: Roughly 2.75 kg CO<sub>2</sub> per cubic meter of methane.
- Methane Slippage: About 1% - 2% of the flared gas might leak as methane.

(GHG Protocol & API guidelines).

The proportional estimation method can be used to calculate gaseous emissions resulting from leaks from storage tanks or transmission lines, and is a common method when exact data on leakage quantities is not available. This method is based on international standards that determine estimated leakage rates based on the amount of oil or gas stored or transported. Steps to calculate the carbon footprint by proportional estimation:

1) Leakage percentage: A leakage percentage is determined based on practical experiences and studies. For example:

- Leakage from tanks: Ranges from 0.01% to 0.1% of the amount stored per year, depending on the type of tank and the level of maintenance.
- Leakage from transportation lines: 0.005% to 0.05% of the amount transported.

2) Calculate the amount of escaping gas: If the amount stored or transported is known, the amount of escaping gas is calculated using the equation:

$$Q_{\text{leak}} = Q_{\text{oil/gas}} \times P_{\text{leak}} \quad (4)$$

(GHG Protocol and API guidelines)

Where:

- $Q_{\text{leak}}$ : amount of leakage gas.
- $Q_{\text{oil/gas}}$ : The amount of oil or gas stored or transported.
- $P_{\text{leak}}$ : Percentage of leakage.

3) Distribution of fugitive gases:

- Determine the percentages of fugitive gases (methane, carbon dioxide, etc.).
- For example:

Methane makes up about 80% - 90% of fugitive gases in natural gas systems.

Carbon dioxide makes up a larger percentage in crude oil.

4) Conversion to CO<sub>2</sub> equivalent: Global warming factors (GWP) are used to convert the calculated amounts into CO<sub>2</sub> equivalent

$$\text{CO}_2\text{e} = Q_{\text{leak}} \times \text{GPW} \quad (5)$$

(GHG Protocol & API guidelines).

Correlation and Regression Analysis can be used to study relationships between specific activities (e.g., energy consumption, transport use) and carbon emissions. By examining historical data, organizations can establish which activities are most closely associated with increased emissions, helping identify critical areas for improvement.

Correlation Coefficient Range:

- $-1 \leq r \leq 1$ , ( $r = 1$ : Perfect positive linear correlation. &  $r = -1$ : Perfect negative linear correlation. &  $r = 0$ : No linear correlation.
- Acceptable Values: In most practical applications, an  $r$  value above 0.7 or below  $-0.7$  is considered a strong correlation.
- Moderate correlation: |between 0.5 and 0.7.
- Weak correlation:  $|r|$  below 0.5.

- $R^2$ : Coefficient of Determination Range  $0 \leq R^2 \leq 10$
- $R^2 = 1$ : Perfect fit; all data points lie on the regression line.
- $R^2 = 0$ : The model explains none of the variability in the dependent variable.

Acceptable Values:

- $R^2 > 0.7$ : Generally acceptable in most research fields.
- $R^2 > 0.9$ : Indicates a very strong fit, common in controlled experiments.
- $R^2$  between 0.4 and 0.7 may be acceptable in fields like social sciences, where variability is higher.

### 3. Result and Discussion

To figure out what drives greenhouse gas emissions (the carbon footprint) linked to crude oil and natural gas production, first all the activities were sorted into different operational boundaries—specifically, scopes 1, 2, and 3, along with their subcategories. After that, the carbon footprint was calculated for each of those activities. In the second step, the relationships between all the potential factors as independent variables and the carbon footprint as the dependent variable mapped out. Then, we figured out the main trends that emerged from that data.

**Figure 2** shows how the carbon footprint from crude oil and natural gas production at all of Khalda Petroleum's sites in Egypt's southern desert stacks up. It's pretty clear that flaring gases make up a big chunk of the carbon emissions, then diesel use in generators and transportation. On the flip side, water supply and refrigerants contribute the least. Meanwhile, using natural gas in turbines and heaters, along with venting gases, falls somewhere in the middle when it comes to their impact.

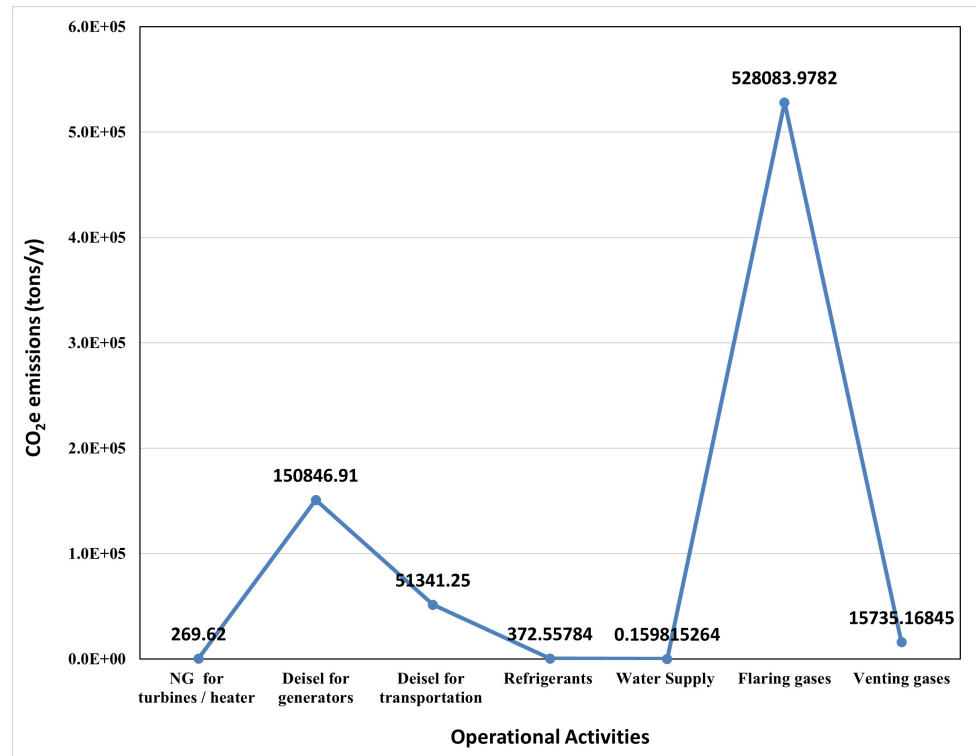
It's pretty clear that the main problems here are tied to the greenhouse gas emissions from fuel use, whether that's from burning it in engines or letting it vent during the storage and transport of crude oil and natural gas. Plus, there's also the flaring to manage pressure and keep air pollution in check.

So, looking at earlier notes, all the dependent variables will dive into and to see how they connect with the carbon footprint. The aim is to identify the various types of relationships and highlight the key trends that emerge. It really about understands how everything fits together in the broader context.

KPC is producing around 23,300,565 barrels of crude oil each year. It's roughly equivalent to about 136.6 trillion MJ of energy. On the other hand, they're also pumping out about 162534.5 mmcf of natural gas annually, which adds up to around 171.5 trillion MJ. Their total energy production is estimated at about 307.5 trillion MJ.

It's important to keep in mind that all this production comes with its own environmental impact. KPC's operations contribute around 746.65 billion grams of CO<sub>2</sub>e emissions each year. If you look at it from a carbon footprint perspective, that translates to roughly 2.42 grams of CO<sub>2</sub>e for every MJ of energy produced.

Some interesting insights on how crude oil and natural gas production contribute to greenhouse gas emissions. Here's what some studies have uncovered:



**Figure 2.** Amount of GHG emissions from crude oil and natural gas production at all Khalda Petroleum company.

- A study from **Stanford University in 2015** found that, on average, crude oil production releases around 10.3 grams of carbon for every megajoule of oil produced. That's a pretty significant figure when you think about it. <https://www.dw.com> (2015).
- Another study from **Stanford's School of Earth, Energy and Environmental Sciences (2018)**, published in 2018, highlighted that countries with high carbon footprints emit over 15 grams of carbon dioxide equivalent for each megajoule of crude oil. <https://news.stanford.edu> (2018).
- Lastly, a report from **the International Council on Clean Transportation (2010)** back in 2010 titled "Carbon Intensity of Crude Oil in Europe" found that the carbon intensity of crude oil can vary quite a bit, ranging from 4 to 50 grams of carbon dioxide equivalent per megajoule. <https://theicct.org> (2010).

It's pretty clear that KPC's operations aren't making much of a dent compared to the global average. This might be because their estimates of greenhouse gas emissions from venting gases aren't super accurate. They've based those numbers on the percentage of natural gas and crude oil that's stored or transported, but without solid data to back it up, it's hard to get a clear picture.

### 3.1. Relationships and Main Trend

#### 3.1.1. Linear Relationships

Fit a linear equation, a linear relationship can generally be represented as:

$$\text{CO}_2 \text{ emissions} = a \times \text{Fuel consumption} + b \quad (6)$$

where  $a$  is the slope (rate of increase in emissions per unit of fuel) and  $b$  is the intercept (emissions when fuel consumption is zero).

To figure out the slope and intercept using the provided data points, you can estimate the slope ' $a$ ' by calculating the change in CO<sub>2</sub> emissions divided by the change in fuel consumption. In simpler terms, it looks like this:

$$a = \Delta(\text{CO}_2 \text{ emissions}) / \Delta(\text{fuel consumption}) \quad (7)$$

By calculating the slope and using one of the points to solve for  $b$ , solid model can be creating a model that approximates the relationship between CO<sub>2</sub> emissions and fuel consumption. Here's **Table 2** that breaks down descriptions of dependent variables, correlation coefficient and its acceptability.

**Table 2.** Description of dependent variables, correlation coefficient and acceptability.

Dependent Variables	r	R <sup>2</sup>	Description	Acceptability
Consumption of NG in turbines and heaters as a fuel	+	1	<ul style="list-style-type: none"> <li>Perfect positive linear correlation.</li> <li>Percentage of variations in independent variable due to dependent variable is almost 100%.</li> </ul>	strong correlation
Consumption of Diesel in in generators and pumps as a fuel.	+	1	<ul style="list-style-type: none"> <li>Perfect positive linear correlation.</li> <li>Percentage of variations in independent variable due to dependent variable is almost 99%.</li> </ul>	strong correlation
Consumption of diesel in generators and pumps as a fuel.	+	0.99	<ul style="list-style-type: none"> <li>Perfect positive linear correlation.</li> <li>Percentage of variations in independent variable due to dependent variable is almost 99%.</li> </ul>	strong correlation
Consumption of water supply.	+	1		strong correlation
Flaring gases	+	1		
Venting from storage oil	+	1	<ul style="list-style-type: none"> <li>Perfect positive linear correlation.</li> <li>Percentage of variations in independent variable due to dependent variable is almost 100%.</li> </ul>	strong correlation
Venting from storage NG	+	1		
Venting from transported oil	+	1		
Venting from transported NG	+	1		

In **Table 2**, you'll find the key parameters that define the nature of these relationships. The data presented in the table shows that all the dependent variables related to natural gas (NG), diesel consumption across various activities, and the flaring and venting of gases are strongly linked to greenhouse gas (GHG) emissions. These relationships are positively linear and quite significant. The independent variable, CO<sub>2</sub>e, accounts for nearly 100% of the variation, indicating a perfect fit with an R<sup>2</sup> value of 1. This means that all the data points fall right on the regression line.

According to various relationships, **Figures 3-11** show the connections between different sources of fuel consumption, venting, and flaring.

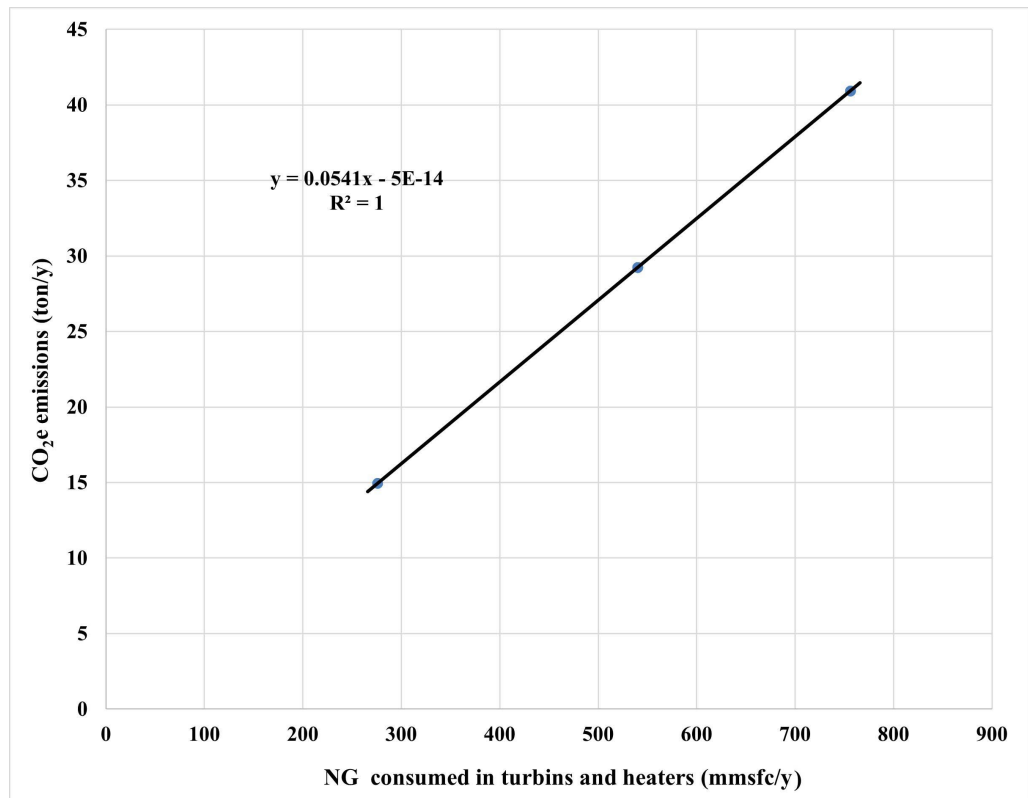


Figure 3. Correlation between NG fuel used in turbines and heater and CO<sub>2</sub>e emissions.

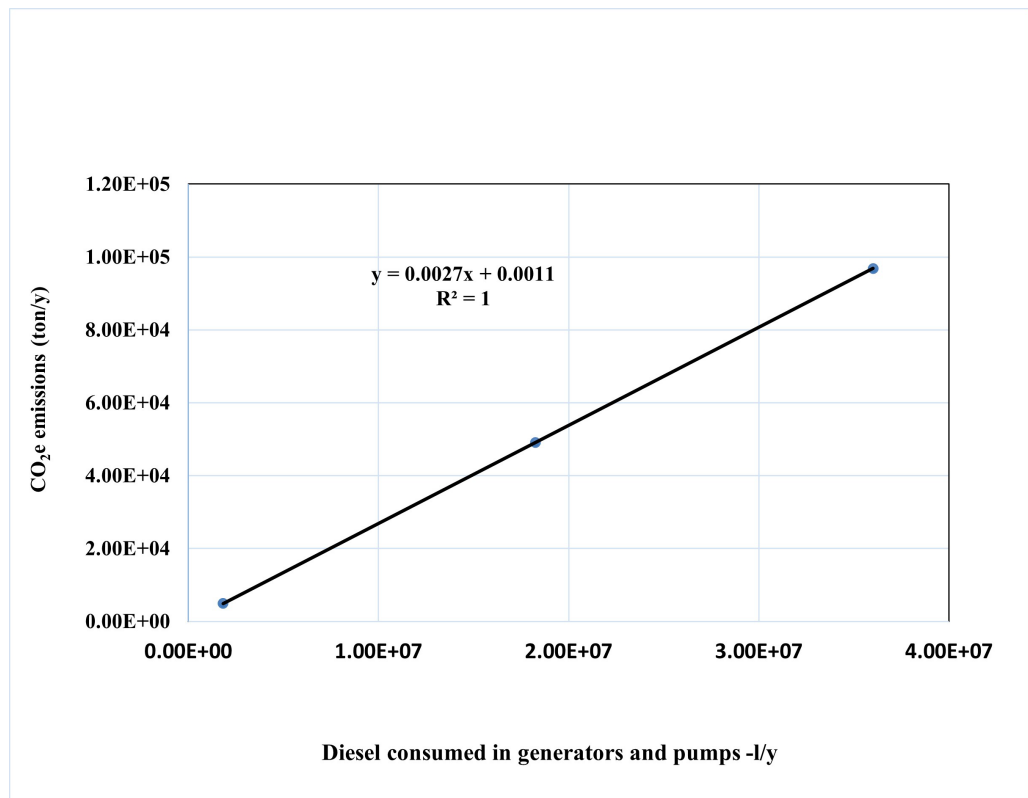


Figure 4. Correlation between diesel fuel used in generators and pumps and CO<sub>2</sub>e emissions.

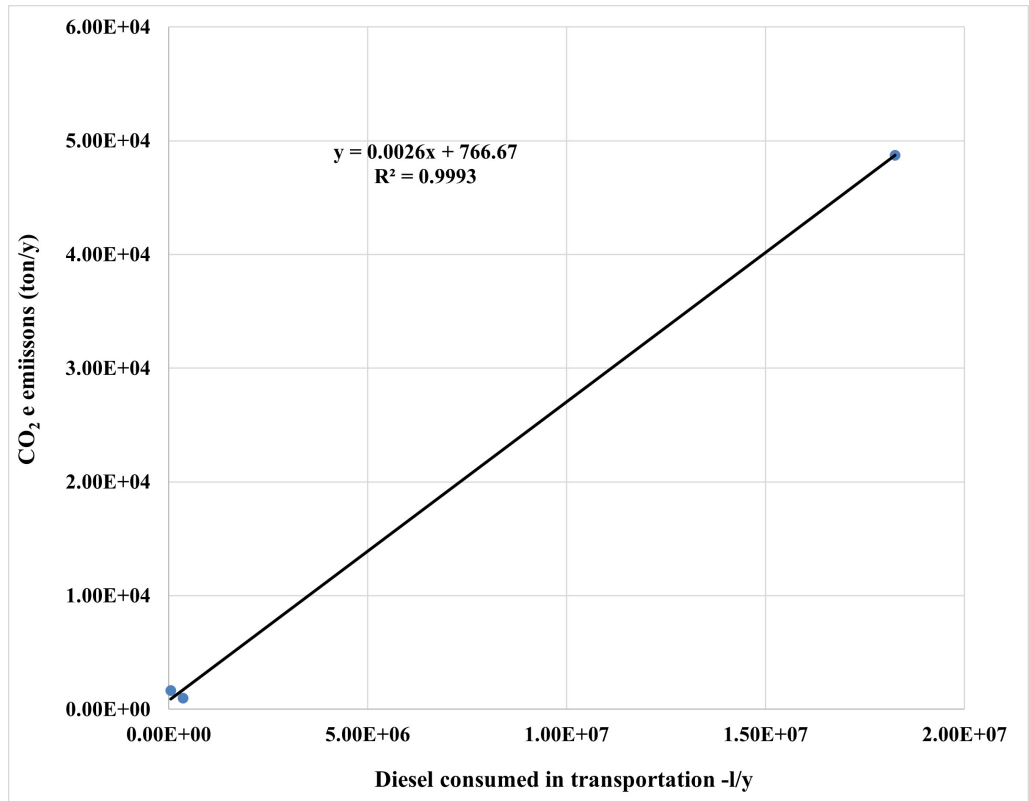


Figure 5. Correlation between diesel fuel used in transportation and CO<sub>2</sub>e emissions.

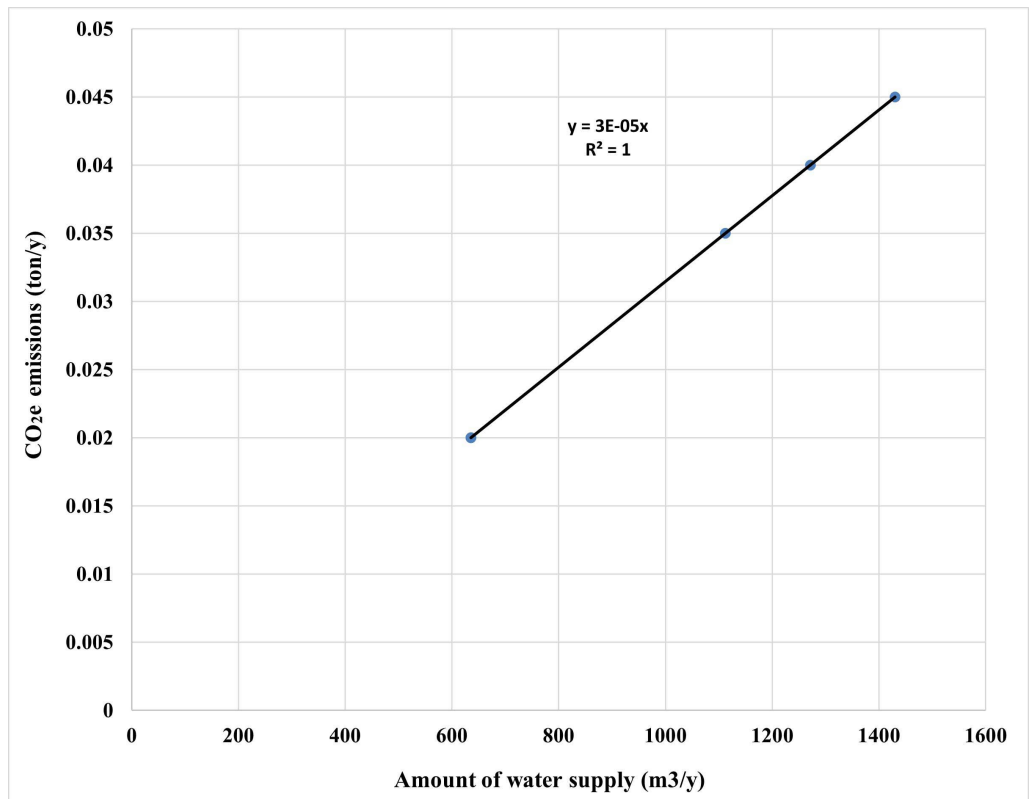
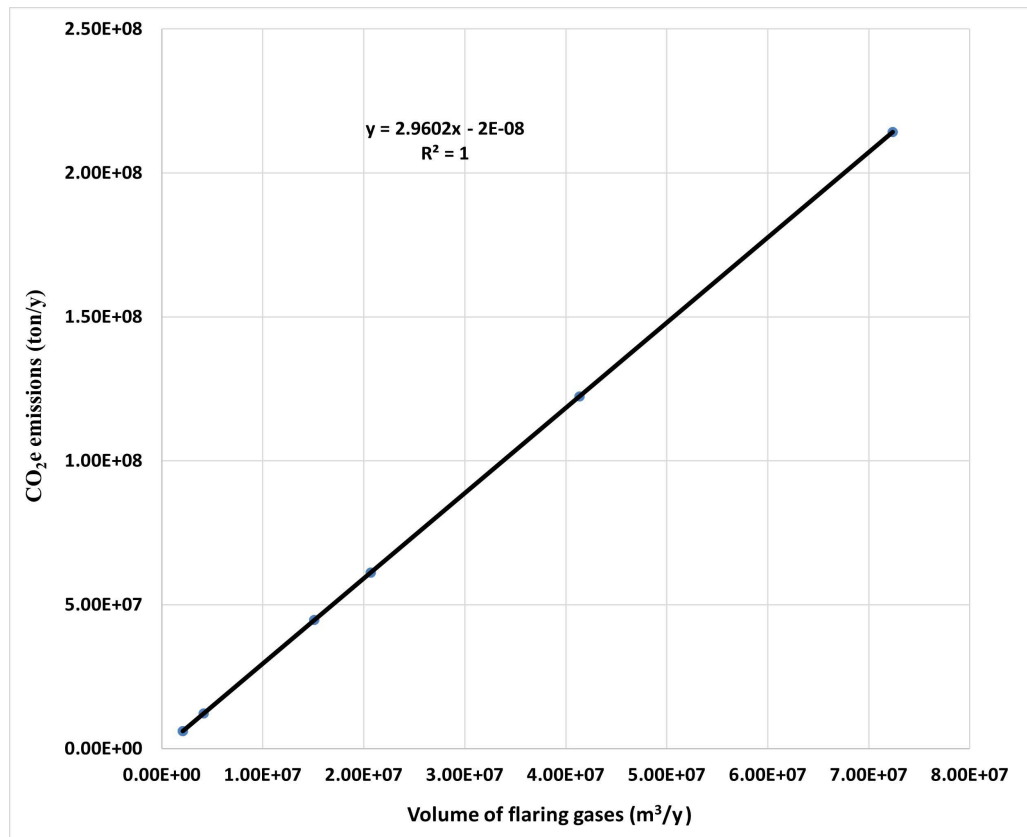
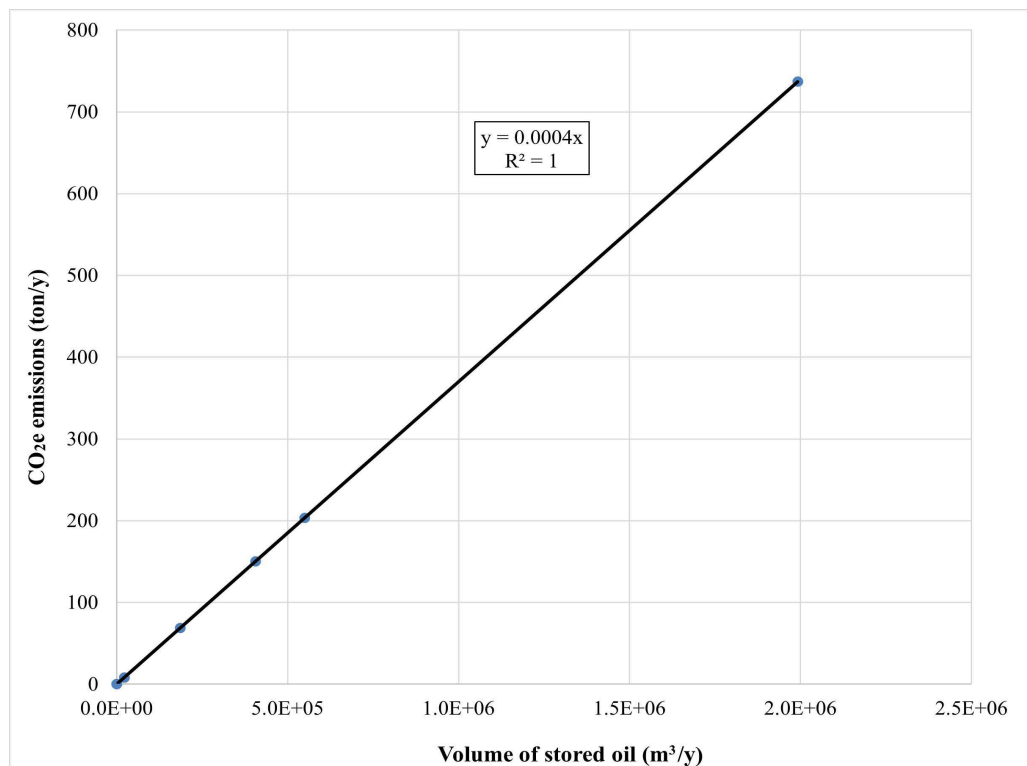


Figure 6. Correlation between amount of water supply and CO<sub>2</sub>e emissions.



**Figure 7.** Correlation between volume of flaring gases and CO<sub>2</sub>e emissions.



**Figure 8.** Correlation between venting gases from storage crude oil and CO<sub>2</sub>e emissions.

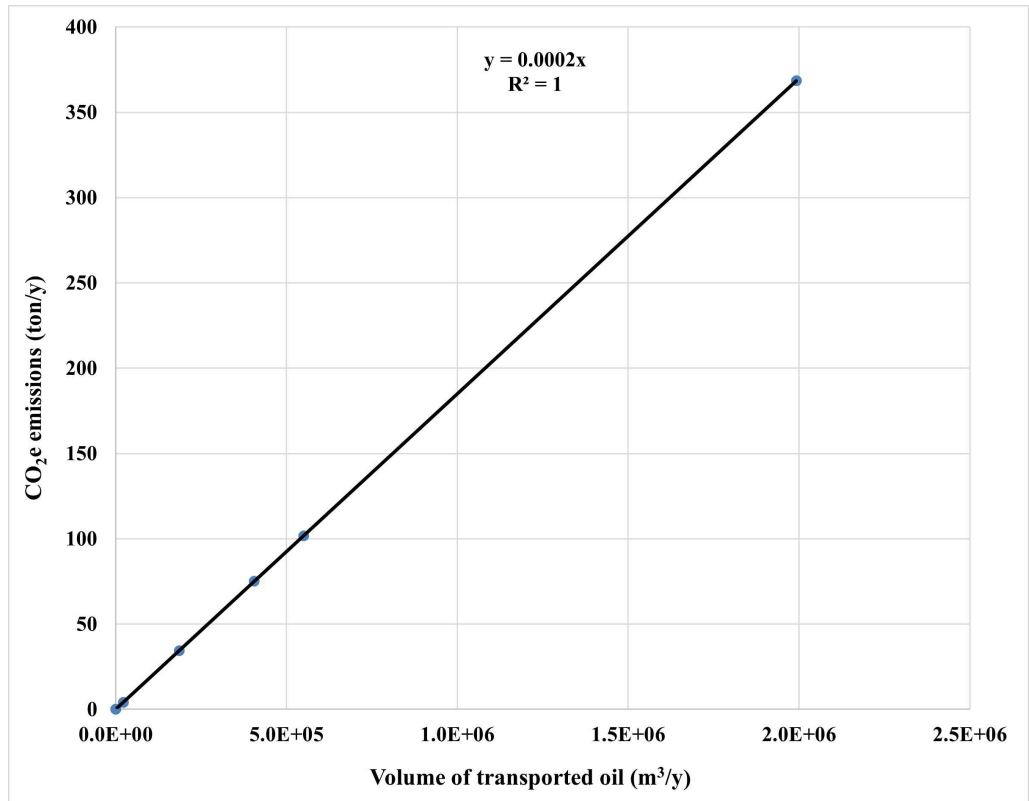


Figure 9. Correlation between venting gases from transported crude oil and CO<sub>2</sub>e emissions.

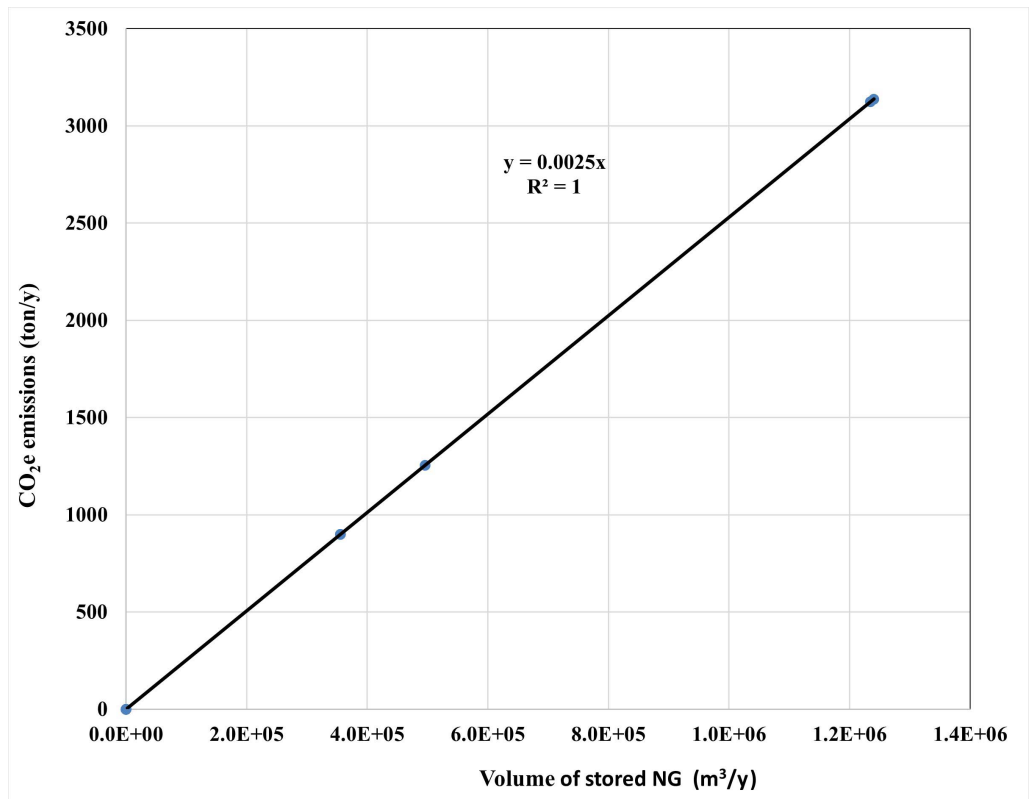
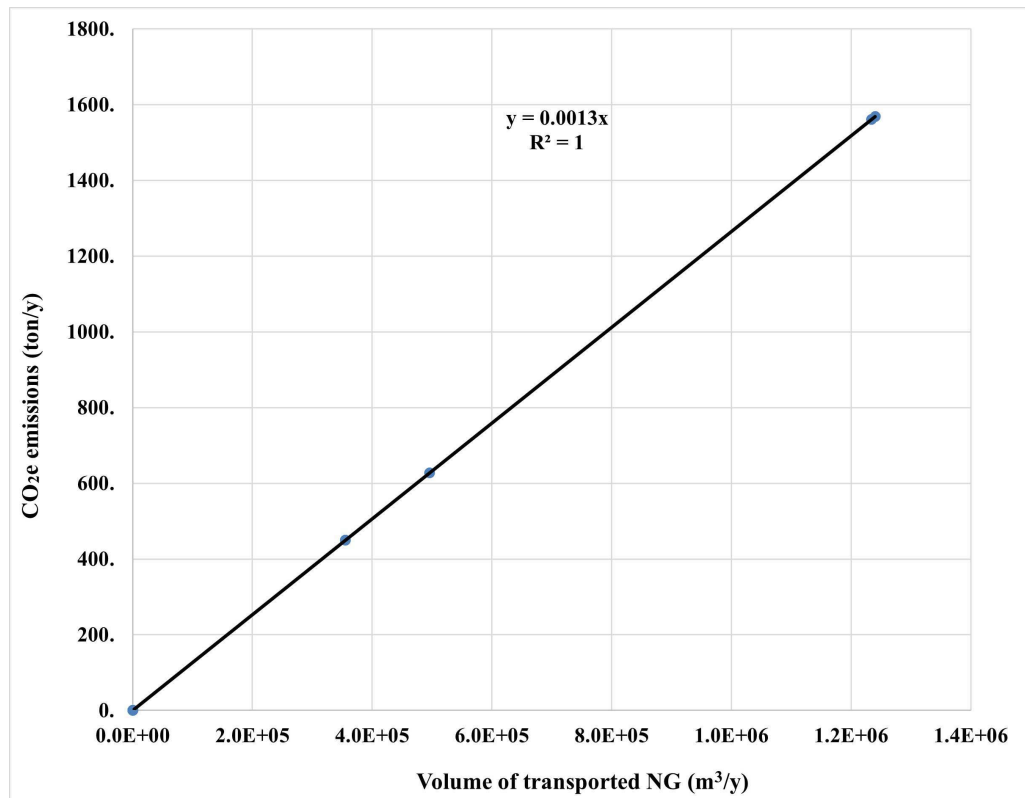


Figure 10. Correlation between venting gases from NG storage tanks and CO<sub>2</sub>e emissions.



**Figure 11.** Correlation between venting gases from transported NG and CO<sub>2</sub>e emissions.

### 3.1.2. Polynomial Relationship

A polynomial relationship refers to a mathematical expression where the dependent variable is related to the independent variable(s) by a polynomial equation. A polynomial relationship means that the connection between (x) and (y) isn't just a simple straight line; it involves curves and has a bit more complexity. Basically, how (y) changes as (x) changes isn't steady—it can ramp up or down in a non-linear way.

In examining the relationship between the independent variable—GHG emissions—and the dependent variable, which includes the number of combustion devices (like turbines and heaters), we found that the coefficient of determination ( $r^2$ ) was quite low at 0.4159, falling short of the acceptable threshold of 0.5. To improve this, we added the fuel consumption per combustion device as an additional dependent variable. This change boosted the percentage of variation in the independent variable explained by the dependent variable to 0.6762, a significant improvement. **Figure 12** illustrates the connection between the number of combustion devices, their fuel consumption, and GHG emissions.

When we examine the correlation coefficient,  $r = 0.8223$ , it indicates that the relationship between independent and dependent variables isn't perfectly linear. Instead, we're looking at a polynomial relationship, specifically one that is sixth-degree.

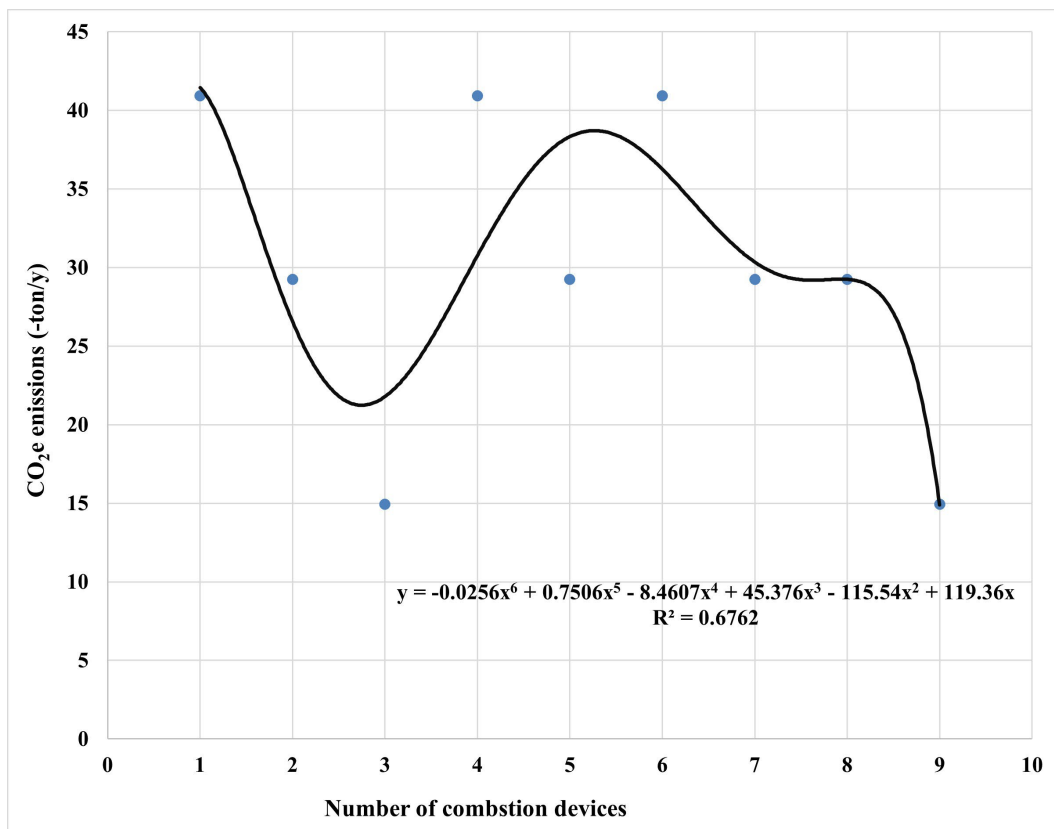
$r^2$  which comes in at 0.6762. This suggests that roughly 70% of the variations in

the independent variable can be linked to changes in the dependent variable. Pretty intriguing,

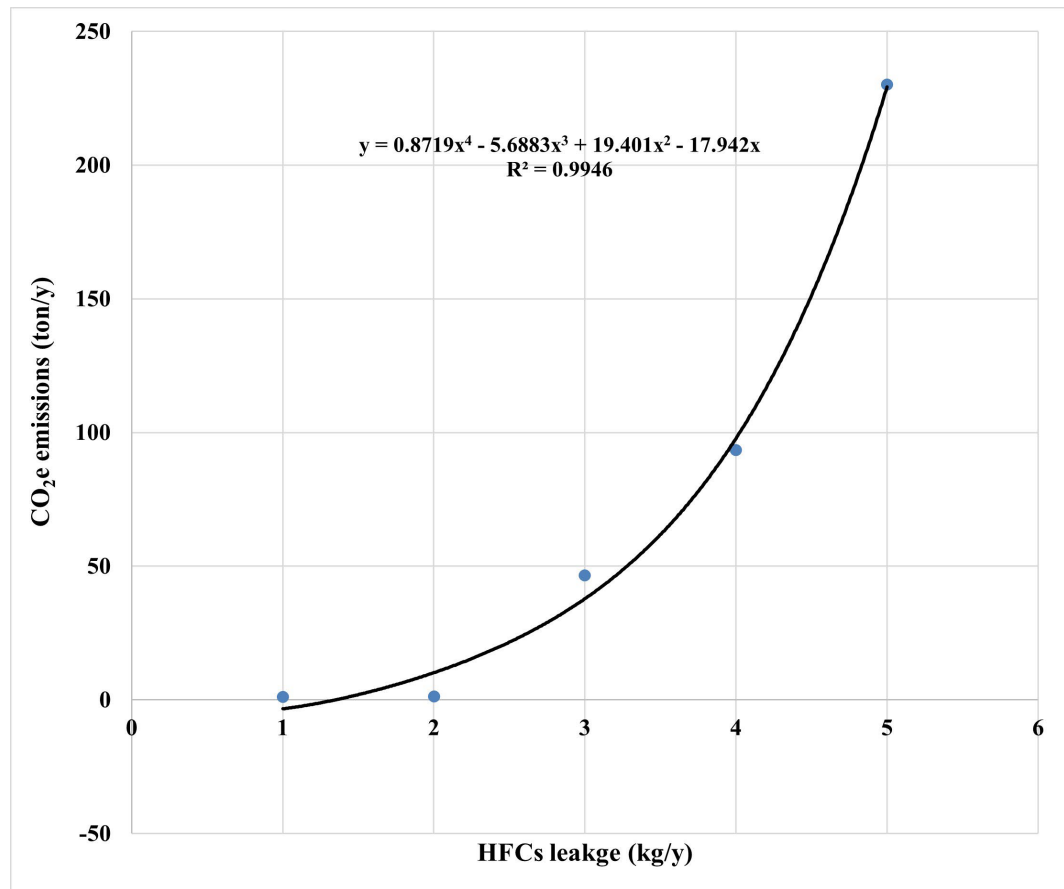
What’s particularly interesting here is how greenhouse gases play into this. It turns out that the amount of these gases released into the atmosphere is mainly affected by the efficiency of our combustion devices rather than just their numbers. So, even if there are fewer devices operating, they can still significantly impact greenhouse gas emissions. It’s really all about efficiency!

As shown in **Figure 13**, the correlation coefficient was analyzed, yielding an r value of 0.9973. This indicates that while there is a strong relationship between the independent variable (CO<sub>2</sub>e) and the dependent variable (the amount of leaked HCFs), it’s not a straightforward linear connection. Instead, we’re dealing with a fourth-degree polynomial relationship.

The r<sup>2</sup> value stands at 0.9946, suggesting that nearly all variations in the independent variable can be attributed to changes in the dependent variable. That’s pretty fascinating! What’s especially noteworthy here is the role of greenhouse gases. It turns out that the amount of these gases released into the atmosphere is primarily influenced by the capacity and efficiency of refrigerant devices and the types of HCFs used, rather than just the number of devices in operation. So, even if there are fewer devices running, they can still have a significant impact on greenhouse gas emissions. It really boils down to efficiency.



**Figure 12.** Correlation between number of combustion devices and fuel consumption and CO<sub>2</sub>e.



**Figure 13.** Correlation between HFCs leakage and CO<sub>2</sub>e emissions.

#### 4. Conclusion

This study provides a comprehensive analysis of the factors driving greenhouse gas (GHG) emissions, specifically focusing on crude oil and natural gas production operations at Khalda Petroleum Company in Egypt's southern desert. The findings reveal key insights into the sources and relationships associated with carbon footprints:

- Flaring gases contribute significantly to overall emissions, followed by diesel consumption in generators and transportation activities.
- Water supply and refrigerants have minimal impact, while natural gas usage in turbines and heaters, along with venting gases, and represent moderate contributors.
- Strong positive linear correlations were observed between fuel consumption (e.g., diesel and natural gas) and CO<sub>2</sub> emissions.
- The analysis demonstrated that independent variables like flaring, venting, and diesel consumption in various activities accounted for nearly 100% of the variation in GHG emissions, as indicated by R<sup>2</sup> values close to 1.
- In some cases, the relationships between GHG emissions and influencing factors were non-linear.
- For instance, the connection between the number of combustion devices, their

- fuel consumption, and emissions revealed a sixth-degree polynomial relationship, emphasizing the importance of efficiency over sheer device quantity.
- Similarly, refrigerant leaks exhibited a fourth-degree polynomial relationship, underscoring the role of device efficiency and refrigerant type in determining emissions.
  - Across multiple analyses, efficiency emerged as a critical determinant of GHG emissions. Both combustion and refrigerant devices, even in reduced numbers, can significantly impact emissions if not optimized for performance.
  - Studies reveal significant variations in the carbon intensity of crude oil production, ranging from 4 to 50 grams of CO<sub>2</sub> equivalent per megajoule, depending on the source and region. While global averages often highlight high emissions, the data suggests that KPC's operations are comparatively lower in carbon intensity, justifying their continued emphasis on carbon conservation strategies.

## 5. Recommendations

Based on the analysis of greenhouse gas (GHG) emissions, here are targeted recommendations to address key emission sources and improve overall environmental performance:

- 1) Address Flaring Emissions (Major Contributor)
  - Adopt Advanced Flaring Technologies: Use high-efficiency flare systems to minimize gas loss and reduce emissions.
  - Implement Flare Gas Recovery Systems: Capture and reuse flared gases as a source of energy or raw material.
  - Optimize Pressure Management: Deploy advanced pressure management systems to reduce the need for flaring during production surges.
- 2) Improve Diesel Consumption Efficiency
  - Switch to Cleaner Fuels: Transition from diesel to lower-carbon alternatives such as natural gas or biodiesel.
  - Upgrade Generators and Pumps: Replace outdated diesel generators with energy-efficient or hybrid models.
  - Regular Maintenance: Ensure generators and pumps are maintained regularly to operate at peak efficiency.
  - Promote Electrification: Where feasible, replace diesel-powered equipment with electric alternatives powered by renewable energy sources.
- 3) Enhance Venting Practices
  - Install Vapor Recovery Units (VRUs): Capture and store gases vented during crude oil and natural gas storage and transportation.
  - Use Sealed Storage Systems: Implement advanced storage technologies to minimize venting from tanks.
- 4) Optimize Natural Gas Usage
  - Upgrade Combustion Devices: Invest in high-efficiency turbines and heaters that consume less natural gas while maintaining output.

- Adopt Low-NOx Burners: Reduce nitrogen oxide emissions by using advanced burners that also improve combustion efficiency.
- 5) Refrigerants and Water Supply (Minor Contributors)
- Transition to Low-GWP Refrigerants: Replace high-GWP (Global Warming Potential) refrigerants with low-impact alternatives.
  - Enhance Refrigerant System Maintenance: Prevent leaks through regular inspections and servicing.
  - Optimize Water Usage: Implement water recycling systems to reduce the carbon footprint of water supply operations.
- 6) Efficiency Improvements
- Conduct Energy Audits: Regularly assess energy consumption and identify opportunities for efficiency gains.
  - Deploy Real-Time Monitoring Systems: Use IoT-based sensors to track fuel consumption, flaring, and venting in real time, enabling swift corrective actions.
- 7) Adopt Renewable Energy
- Integrate Renewable Energy Sources: Invest in solar or wind power installations to supply electricity for operations.
  - Hybrid Solutions: Combine renewable energy with existing systems to reduce reliance on fossil fuels.
- 8) Employee Training and Awareness
- Training Programs: Educate staff on best practices to reduce emissions, such as proper equipment use and fuel-saving techniques.
  - Incentivize Emission Reduction: Reward employees and teams who implement successful emission-reduction measures.
- 9) Policy and Collaboration
- Align with International Standards: Comply with frameworks like ISO 14064 (GHG Accounting) and adopt science-based targets.
  - Engage Stakeholders: Collaborate with industry partners, regulators, and communities to develop sustainable solutions.
- 10) Continuous Monitoring and Reporting
- Track Progress: Regularly measure GHG emissions and compare them against set targets.
  - Transparent Reporting: Publish emission data and reduction initiatives to build trust with stakeholders and enhance accountability.

By implementing these recommendations, Khalda Petroleum can significantly reduce its greenhouse gas emissions, minimize its environmental impact, and align with global sustainability goals.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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