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A comparative assessment of open flame flares and enclosed ground flares for cleaner and safer hydrocarbon production in Mexico

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FIRMA

Dedications:

In loving memory of ***Artemisa*** and ***Loyda Deyanira***

To my family for their love and support:
Carla, Pablo, Sergio, Irma, Lorena, Sergio Eduardo, "the shark friends", Lucy and Hanna

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List of nomenclature and abbreviations.

Alkane hydrocarbons	C_nH_{2n+2}
American Petroleum Institute	API
Billion	1,000 million
Black Carbon	BC
Capital Cost Expenditures	CAPEX
Carbon dioxide	CO_2
Carbon monoxide	CO
Combustion Efficiency	CE
Coordinates of the flame center	(x_c, y_c)
Consequence Analysis	CA
Det Norske Veritas	DNV
Emissivity	ε
Enclosed Ground Flare	EGF
Excess/deficit of air	δ
Flame length	L_f
Flare height	H
Flow rate	φ
Flow stream velocity at exit	V_{exit}
Global Warming	GLW
Health-Environment-Safety	HES
Hydrogen sulfide	H_2S
Inclination angle	θ
intended Nationally Determined Contribution	iNDC
Intergovernmental Panel on Climate Change	IPCC
International Energy Agency	IEA
Thousand tons (1000 tons)	kt

Million tons (1,000,000 tons)	Mt
Methane	CH_4
Net Heating Value	NHV
Nitrogen	N_2
Nitrogen dioxide	NO_2
Nitrogen monoxide	NO
Nitrogen oxides	NOx
Oil and Gas	O&G
Operating Lifetime	OLT
Operating and Maintenance	O&M
Open Flame Flare	OFF
Operational and maintenance expenditures	OPEX
Particulate Matter in sizes of 10, 2.5 or 1 µm	$PM_{10,\ 2.5,\ 1}$
PEMEX Nationally Appropriate Mitigation Action	PEMEX NAMA
Petróleos Mexicanos	PEMEX
Polycyclic Aromatic Hydrocarbons	PAH
Pressure drop	ΔP
Process Hazard Analysis Software Tool	PHAST
Risk Analysis	RA
Sulfur dioxide	SO_2
Sulfur oxides	SOx
Thermal Oxidizer	THO
Thermal Radiation Intensity	I
Thermal Safety Radius	R
United States of America	USA
United States Patent and Trade Office	USPTO
Visible Infrared Imaging Radiometer Suite	VIIRS

Volatile organic compounds	VOC
Wind velocity	V_{wind}

A comparative assessment of open flame flares and enclosed ground flares for cleaner and safer hydrocarbon production in Mexico

Abstract

Hydrocarbon industry flaring practices emit large amounts of unburned hydrocarbons and climate forcers, creating environmental and social impacts. The objective of this study is to thoroughly compare different flaring technologies in situations where the industry is unable to avoid flaring. An integrated methodology for assessing two flare technologies in terms of Health-Environment-Safety (HES) impacts, economic performance, and safety benefits is proposed. The methodology includes stoichiometric calculations of combustion reactions, pollutants emission estimation, flare dimensioning for an equivalent inflow stream to be flared, and economic scenarios for assessing Enclosed Ground Flares (EGFs) versus Open Flame Flares (OFFs). The methodology was applied to a Mexican hydrocarbon installation that currently operates OFFs with a historical record of low combustion efficiency. If an EGF were to replace the existing OFF, there would be a significant emissions abatement that depends on their realistic operating efficiencies. Furthermore, the EGF has the potential to utilize over 1 GW of thermal power for energy use on site such as Combined Heat Power (CHP) applications, which is currently being wasted as the OFF releases it into the environment by typically flaring at most 3.75 Mm^3/d in the Samaria II Compressors case study. The safety radius required for the Samaria II OFF is 7.7 to 8.8 times that required for the EGF of equivalent capacity. Over a 30-year period for the case study, the cumulative investment and Operating and Maintenance (O&M) costs for EGF are about 23% less than for OFF. It was determined that for the Samaria II case study the EGF's ratio of total expenditures vs avoided emissions in a 30-year period is 0.13 USD/tCO_2e. Whereas for the Cunduacan case study the EGF's ratio is 0.18 USD/tCO_2e. In both cases OFF's resulting ratio is much higher than the EGF's number. The consequence analysis with the PHAST software found that various failure conditions can be contained within the EGF combustion chamber without causing significant damage to the facility. However, the impacts of disturbances in the OFF such as gas clouds, flash fires, and explosions are around the torch. All these findings indicate that replacing OFF with EGF would be a safer and more economical solution in the future, as it also helps reduce pollutant emissions being also a mitigation action against global warming.

Keywords:

Enclosed flares techno-economic assessment; Flare combustion efficiency; Flaring safety area; Gas flare safety; Hydrocarbon flaring emissions.

1. Introduction

Gas flaring is a practice that has prevailed in the oil and gas (O&G) industry for over 160 years (The World Bank Group, 2021). As recently as 2019, about 150 billion m^3 of gas were burned worldwide (The World Bank Group, 2020). This practice is no longer sustainable (Hamidzadeh Z. , Sattari, Soltanieh, & Vatani, 2020) due to its harsh environmental consequences (Intergovernmental Panel on Climate Change. Working Group II, 2022). Since 2012, the Visible Infrared Imaging Radiometer Suite (VIIRS) has globally detected in operation over 10,000 gas flares per year (The World Bank Group, 2020). Despite the need for decarbonization and Global Warming (GLW) mitigation, the demand for O&G continues to increase worldwide, and this trend will continue far beyond 2050 (International Energy Agency, 2022).

At present, Mexico is the 8th largest gas-flaring country in the world, contributing 5.77 billion m^3 of flared gas in 2020 (The World Bank Group, 2021). According to PEMEX[1], 6.3 billion m^3 of gas was released into the atmosphere due to its production activities in 2021 (Petróleos Mexicanos, 2021). Between 2018 and 2021, Mexico increased the volume of CH_4 released into the atmosphere by 62% (Petróleos Mexicanos, 2021), and this tendency continues. Currently, with the exception of three EGFs implemented in a Refinery, PEMEX mostly employs Open Flame Flare (OFF) technologies. However, the environmental and operational benefits achievable when deploying Enclosed Ground Flare (EGF) technologies, must be analyzed by the decision-makers with the aim to contribute to the mitigation of the GLW crisis.

Flare technologies can be classified by the height of the flare tip over the ground level and categorized into two major groups such as elevated or ground flares (Sorrels, Coburn, Bradley, & Randall, 2019). OFFs mostly correspond to elevated flares, which also can be subclassified into different types such as steam-assisted, air-assisted, pressure-assisted, or non-assisted (Sorrels, Coburn, Bradley, & Randall, 2019) (Straitz III J. F., 1994). When flares combust a hydrocarbon mixture at ground level, they can be subclassified as either Enclosed or Open Ground Flares (OGF) (Fluenta, 2018). OGFs mostly correspond to pit flares whereas EGFs conceal the flames from a direct view within a combustion chamber at ground level (Bader, Adam; Baukal, Charles E. Jr.; Bussman, Wess, 2011). **Figures 1, 2**, and **3** respectively show examples of OFFs, EGFs, and OGFs in operation. **Figure 4** shows a simplified schematic diagram of a typical combustion chamber of an EGF and its key components. Technical literature also identifies EGFs as vapor combustors or incinerators (Akers, y otros, 09, 1997). Due to space limitations in populated areas, EGFs have been deployed more frequently in the O&G industries in Southeast Asia, Australia, China, Korea (Straitz III & Chua, Enclosed flares: A look inside today's state-of-the-art systems, 1996), Russia, Taiwan, and Europe. EGFs were initially inventions registered before the United States Patent and Trade Office (USPTO) in the '60s and '70s, used in the O&G industry ever since. However, even today EGFs are considered new technologies [13]. There are several brands, patents, processes, and trademarks from different countries of OFFs and EGF systems.

[1] PEMEX is the acronym of the national oil & gas company, Petróleos Mexicanos

Fig. 1. Onshore & Offshore applications of Open Flame Flares (OFFs)
Source: Courtesy pictures by ESISA® & NAO, Inc

Fig. 2. Onshore & Offshore applications of Enclosed Ground Flares (EGFs)
Source: Courtesy pictures by ESISA®& NAO, Inc.

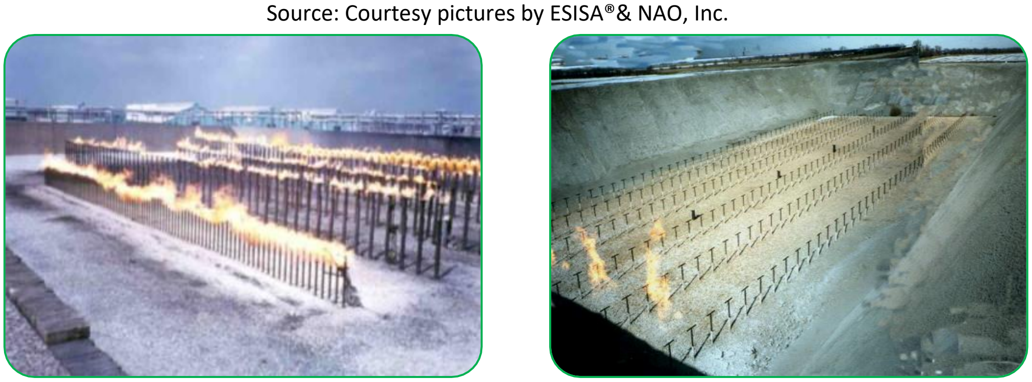

Fig. 3. Onshore applications of Open Ground Flares (OGFs)
Source: Courtesy pictures by ESISA®& NAO, Inc.

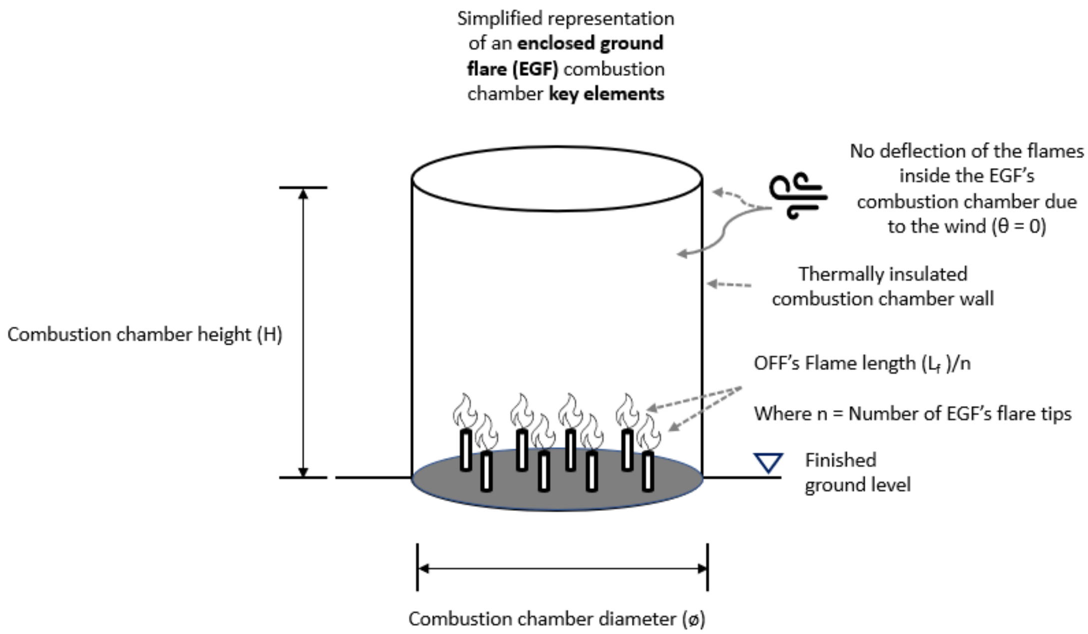

Fig. 4. Simplified schematic diagram of a typical Onshore EGF combustion chamber
Source: Own work

EGFs can be designed not only for combusting a flow stream but can perform as a thermal oxidizer (THO) as well (Straitz III & Chua, Enclosed flares: A look inside today's state-of-the-art systems, 1996); however, this option is outside the scope of this study. EGFs can take advantage of the combustion heat concentrated in the combustion chamber (Wu, Wei, Gao, Han, & Weijian, 2019) with additional equipment downstream, such as a Combustion-Heat-and-Power (CHP) generation system.

During EGFs' regular operation, acoustic and luminous radiation is avoided which does not occur in OFFs. Both radiations have important impacts on personnel, equipment, and ecosystems inside and outside the facility. Combustion noise from flaring is generated by the flow rate operating discharge pressure and water vapor contents if any (Straitz III J. F., Burner noise and its suppression, 1991). Thermal and acoustic radiation are due to process conditions, and they cannot be separated from each other. Reducing thermal, acoustic, and luminous radiation through the implementation of EGFs is an added benefit that the facility owners and the stakeholders should be looking for as well.

Regardless of the technology employed, flaring a hydrocarbon gas mixture should convert flammable and hazardous compounds into less dangerous oxidized combustion products such as CO_2 and H_2O to maintain safe conditions in hydrocarbon plants (Mohabbat, Pirouzfar, & Sakhaeinia, 2017) (Outomuro Somozas, Nielsen, Maschietti, & Andreasen, 2020). When flaring is performed by incomplete combustion, other hazardous pollutants are also released into the atmosphere, such as methane (CH_4), black carbon (BC, soot in the form of Particulate Matter in sizes of 10, 2.5 or 1 µm = $PM_{10,\ 2.5,\ 1}$), carbon monoxide (CO), sulfur dioxide (SO_2), sulfur oxides (SOx), nitrogen oxides (NOx), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAH) and unburned hydrocarbons (European Union, 2014). Usually released flue gases interact directly or indirectly with other compounds and aerosols present in the atmosphere, simultaneously affecting air quality and the natural climate processes (Fawole, Cai, & MacKenzie, 2016).

The hydrocarbon industry is looking for CH_4 emission reductions since O&G extraction, transformation, and distribution activities are responsible for up to 23% of global anthropogenic methane emissions whereas CH_4 increases the speed of GLW atmospheric processes (Climate and Clean Air Coalition, 2022). Generally, precise information about the compositions of hydrocarbon gas mixtures is poor and often not public. Consequently, information about emissions of specific compounds such as sulfur dioxide (SO_2), nitric oxide (NO), and nitrogen dioxide (NO_2) is usually not included in the emission inventories of hydrocarbon producers (Fawole, Cai, & MacKenzie, 2016) (Fioletov, et al., 2016).

In 2016 Mexico signed the Paris Agreement, committing to reducing 2013 GHG emissions by 22% by 2050 (Gobierno de la República, México, 2015). Particularly, the commitment of the O&G sector is to reduce emissions by 14%, which is equivalent to reducing the baseline from 972 to 762 $MtCO_2e$ by 2030 (Gobierno de la República, México, 2015). Currently, the upstream emissions are 22% for onshore, and 52% for offshore facilities, mainly along the Gulf of Mexico coast (Sheng, et al., 2017). Considering this scenario, the PEMEX Nationally Appropriate Mitigation Action (PEMEX NAMA) issued in 2013, focuses mainly on limiting CH_4 fugitive emissions at different points, such as compressors, turbines, valves, seals, and flares, but OFFs continue to be used as traditionally (Petróleos Mexicanos, 2013). Mexico needs to apply a stricter mitigation strategy in the O&G industry to achieve a 50% reduction of GHGs by 2050 (Veysey, et al., 2016).

A recent study released by the International Energy Agency (IEA) states that CH_4 emissions from the energy sector could be 70% higher than the official reports (Climate and Clean Air Coalition, 2022) (International Energy Agency, 2022). This is important to keep in mind, as the Combustion Efficiency (CE) in flares tends to decrease over time if the technologies are not properly designed, operated, and maintained. Hence, pollutant inventories could be higher than expected. OFF technologies are very sensitive to a lack of maintenance (Fluenta, 2018), while EGF technologies are more resilient to heavy-duty operations (Cid-Vazquez & Rodriguez-Tovar, 2013). The decreases in CE imply emissions higher than expected of unburned hazardous hydrocarbons and BC formation as soot. These unburned compounds with a high greenhouse effect, also produce a great environmental and social impact near the facilities as most of them are criteria pollutants as well (The John Zink Hamworthy, 2013) (Banerjee, Cheremisinoff, & Cheremisinoff, 1985).

Upon defining aspects such as the gas mixture parameters along with the operational and maintenance practices, and the degree of sophistication desired for the flare system (Stone, Lynch, Pandullo, Evans, & Vatavuk, 2012) a techno-financial assessment can be performed for better evaluating the flare capabilities suitable for the application case. The information from diverse sources and vendors states that the average lifetime of OFFs' key parts ranges from 6, 10, to 15 years (Sorrels, Coburn, Bradley, & Randall, 2019) (Cid-Vazquez & Rodriguez-Tovar, 2013) depending on operating conditions and maintenance practices. Typically, OFF's average Operating Lifetime (OLT) in critical components such as flare tips, pilots, sensors, control panels, and knock-out drums, is 6 years for PEMEX sites due to operation and maintenance deficiencies or stolen parts (Cid-Vazquez & Rodriguez-Tovar, 2013). Whereas the OLT for EGFs ranges from 25 to 30 years (Carbon Limits AS, 2014) as they are robust and bulky pieces of equipment hard to steal, and resilient to lack of maintenance. Although the initial capital cost expenditures (CAPEX) could be as much as 3 to 5 times higher in EGF technologies than in OFF technologies, the operational and maintenance expenditures (OPEX) along with the replacement cost should be considered as well during the lifetime expected period for performing a fair assessment as discussed in Economic Evaluation Section.

The contribution of this study is to provide a more in-depth analysis of how to assess OFFs and EGFs when flaring cannot be avoided, and production must continue as is the case in Mexico. Therefore, a predictive methodology based on the evaluation of combustion efficiencies, emissions calculations, economic, and safety aspects is discussed in Section 2. This methodology is used to compare and quantify the benefits that OFFs and EGFs can offer to the case under assessment.

This document is organized as follows:

- **Section 1** introduces the subjects and background on what the problem is along with the context of the study and structure of this document.

- **Section 2** provides the methodology for assessing an OFF and its equivalent EGF depending on the selected case studies. OFF and EGF calculations are documented for the case studies along with a simplified HAZOP study and the consequence analysis for the selected flare technologies.

  In this section it is documented the OFF and EGF pollutant emissions estimations performed during this study for both technologies.

  This section also describes different economic and financial indicators obtained when performing the economic evaluation of the OFFs and EGFs in the selected case studies.

  This section summarizes the key findings reached during this investigation along with a comparative assessment between the OFF and EGF technologies analyzes through the case studies.

  A comparative assessment of OFFs and EGFs is presented for the case studies.

- **Section 3** shows visualizations of relevant results

- **Section 4** presents the conclusions of this research work.

- **Section 5** provides a few recommendations due to the attained results of this study that can be used for collateral present and future research works.

- **Section 7** provides a glossary of key concepts if the reader requires further clarification.

- **Section 8** provides references consulted during the elaboration of this document.

1.1 Assessing the problem

Even though Mexico is the 15th largest economy in the world and 2nd in Latin America, the country strongly depends on the Oil and Gas (O&G) commercial activities and the industry led by the Mexican National O&G company: Petróleos Mexicanos (PEMEX). According to the Federal Government, in 2021 the Mexican Energy sector occupied 66th place out of 105 counties in CO_2 pollutant emissions generation. As per the World Bank report, in 2020 Mexico was the 8th largest gas-flaring country in the world. Additionally, it should be noted that Mexico, Russia, and South Africa, are the three largest anthropogenic SO_2 emitters in the world mainly due to their energy sectors. In the quest for sustainability, in 2013 PEMEX issued the PEMEX Nationally Appropriate Mitigation Action (PEMEX NAMA), which focuses mainly on limiting CH_4 fugitive emissions at different points, such as compressors, turbines, valves, seals, and flares, but Open Flame Flares (OFFs) continue to be used as traditional since the beginning of the industry in 1862 (Gobierno de México, 2022). Deploying Enclosed Ground Flares (EGFs) in the Mexican hydrocarbon sector very seldom has been performed and even less studied what the benefits are when implementing EGF-based solutions in fields such as technical, environmental, economic and safety. Therefore, this research work proposes to close that gap by assessing the above said aspects about flare technologies suitable for Mexican facilities.

1.2 Hypothesis

Applying a comprehensive analysis of the effects that efficiency has on combustion reactions in hydrocarbon facilities, it can be shown that replacing the open flame flares currently in use with enclosed ground flares is a sustainable carbon mitigation action that reduces gas pollutants emissions into the atmosphere with environmental, economic, and societal benefits.

1.3 Justification

As said in the introduction, the Mexican O&G sector is committed to reduce emissions by 14%, which is equivalent to reducing the baseline from 972 to 762 MtCO2e by 2030. Currently, the upstream emissions are 22% for onshore, and 52% for offshore facilities, mainly along the Gulf of Mexico coast. However, between 2018 and 2021, PEMEX increased the volume of unburned CH_4 released into the atmosphere by 62%, with harsh environmental consequences for the country. This situation is due mostly to the poor performance of PEMEX facilities and flares, most of the time with maintenance lack, causing Mexico to be allocated in the 8th place of flaring countries in the world. Therefore, it is urgent to address this situation to look for reliable flare technologies that can mitigate the environmental problem caused by the PEMEX flaring practices along with unsuitable or unmaintained flare technologies.

Worth to mention that, currently, not so much research work has been devoted by Mexican universities, academic institutions, and in-field technicians for assessing the technical, environmental, economic and safety impacts of flares in applications where the flare technologies are operating with poor performance, low combustion efficiencies and lack of maintenance as happens across the country in the hydrocarbon sector of Mexico. Hence, it is justified for our study to determine the minimum amount of CO_2 and pollutant emissions that would be avoided for no longer being sent out into the atmosphere in hydrocarbon facilities when replacing the OFFs currently in use by Enclosed Ground

Flares (EGFs). This by considering their resiliency to the combustion efficiency lost due to environment factors such as crosswind as discussed in **Section 2.4.1**. PEMEX owns and operates a wide variety of processes and technologies for its O&G facilities, with OFFs of different kinds installed for upstream (onshore and offshore) and downstream activities. However, PEMEX has not explored yet the potential benefits of deploying EGFs as a mitigation action of GLW and in favor of the O&G industry sustainability. Therefore, the objectives of this research work are defined as follows:

1.4 General Objective

Propose, analyze, and justify a feasible alternative for the reduction of pollutant emissions that occur in the OFFs of hydrocarbon production facilities, through technological substitution based on the use of EGFs that will avoid sending large amounts of short-lived climate-pollutants as unburned alkane gases into the atmosphere, which represents one of the global warming mitigation actions agreed in the Paris Agreement.

1.5 Particular objectives

A. Identify the technical information that better characterizes the process conditions for the selected case studies, calculate the key parameters for their OFFs and propose alternate EGFs able to satisfy the same operating conditions per site.

B. Develop a methodology for performing a comparative assessment between the OFF and the EGF proposed for a given facility based in techno-economic indicators considering a 30-year period of operating lifetime.

C. Through the methodology developed herein, evaluate the technical differences between OFF and EGF in the selected case studies, based on the calculated key parameters for the OFFs' and EGFs' considering their estimated operating lifetime.

D. Perform a simplified HAZOP study, and a consequence analysis for assessing the potential outcomes when upset conditions are taking place in the selected OFF or EGF in the selected case studies.

E. Assess the air pollutant emissions generated by the OFFs and EGFs in the selected case studies in a 30-year period, considering the operating lifetime of each application.

F. Evaluate the economic performance of the OFFs and EGFs in the selected case studies in a 30-year period, considering the operating lifetime of each application.

1.6 Scope

Determine the minimum amount of CO_2 and pollutant emissions that would no longer be sent into the atmosphere in hydrocarbon production facilities, when performing the technological replacement of the OFFs currently used by EGFs based on techno-economic indicators.

1.7 Theoretical framework and research method

The research method applied for developing this study consists of the following steps:

I. Bibliographic research work
II. Developing a State-of-the-art study for hydrocarbon gas flares
III. Analyzing national and international O&G experiences using OFF and EGF technologies
IV. Selecting representative case studies for the Mexican hydrocarbon sector
V. Developing a methodology for performing a comparative assessment of OFFs and EGFs based in techno-economic indicators
VI. Assessing the selected case studies
VII. Reporting the key findings and results attained by applying the proposed methodology.

2. Methodology for assessing OFF and EGF technologies

Selecting a flare system for a specific application is not a simple or easy task, considering the diverse operational, environmental, and safety aspects involved in the decision-making process. Hence, it is necessary to assess the parameters that better represent the general design and performance of OFFs and EGFs. The assessment must include aspects such as high CE performance (mainly for reducing pollutant emissions), flaring areas within the hydrocarbon facility, and economic performance of the investments according to the operating lifetime for each type of flare system.

This research provides key indicators for assessing OFF and EGF technologies operating under similar flaring operating requirements through the methodology depicted in **Figure 5**. The proposed methodology is split into seven major stages for providing a more in-depth analytically congruent assessment. These stages initiate by collecting the case study information (Stage 1). Then perform calculations for OFF's key parameters, alternative EGF's proposal, and its HAZOP study and consequence analysis (Stage 2). Establish the stoichiometric and CE considerations (Stage 3). Evaluate the pollutant emissions by considering the impact of CE (Stage 4). Based on the results attained, perform economic evaluations for OFF vs EGF in the case study (Stage 5). Develop a summary of the key findings (Stage 6). Finally, develop a detailed comparative assessment report (Stage 7). The novelty of this methodology strives in the fact that upon defining an OFF-application case, an alternative EGF can be proposed for assessing which technology could be more suitable for the facility under analysis through techno-economic indicators. The result of this methodology gathers all the relevant information about the assessed flare technologies to provide the stakeholders with concise data for a technically informed decision-making process.

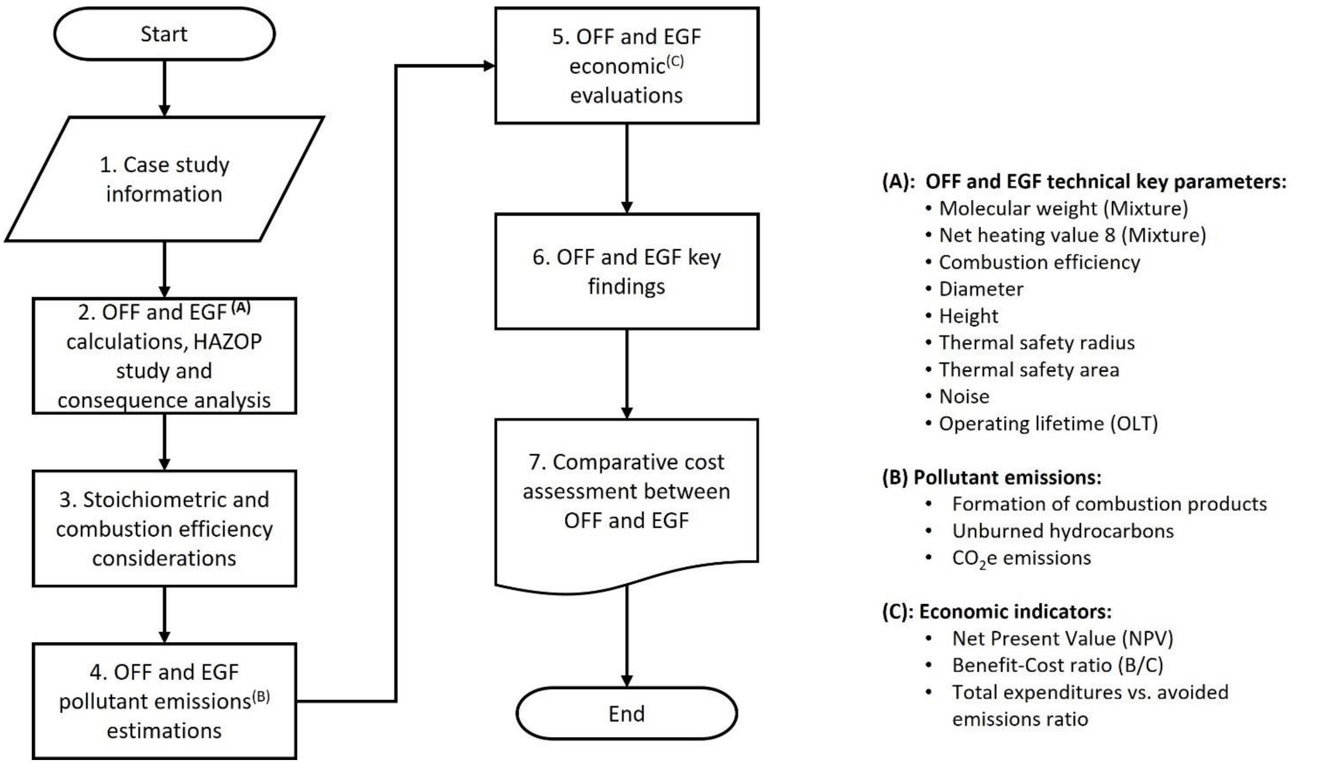

Fig. 5. Methodology for assessing an OFF versus an EGF under similar flaring operating requirements
Source: Own work

2.1 Stage 1. Case study information

Combustion heat release calculations must be performed for the predefined gas mixture as a function of the CE engineered for the flares. In flaring situations, upon defining the key parameters of an OFF, i.e., diameter, height, thermal safety radius, and thermal radiation (heat release) produced during combustion, follows to propose an equivalent EGF for evaluating both technologies under comparable use. Equations described below and during this document provide the modeling base of the sour gas combustion reactions for estimating the key parameters of an OFF, proposing then an equivalent EGF dimensioned under analogous process conditions and flaring operating requirements.

As 40.4% of the onshore O&G production in Mexico is due to the PEMEX Samaria-Luna Production Asset (PSLPA) (Secretaría de Energía (SENER), 2013), the results obtained for OFFs versus the equivalent EGF were addressed for a typical onshore case study within the PSLPA. The selected case studies are the Samaria II and the Cunduacan Compressors Batteries, facilities located in southern Mexico at geographical coordinates: 17.99557 (North); -93.08990 (West) for Samaria II Compressors and 18.06716 (North); -93.09518 (West) for Cunduacan Compressors (PEMEX Exploración y Producción, 2010). The maximum gas flow rate is 3.38 NMm^3/d for Samaria II Compressors and 2.56 NMm^3/d for Cunduacan Compressors, with the typical gas mixture compositions and input data shown in **Table 1.**

Table 1. Case studies gas mixture input data

Concept					Samaria II Compressors	Cunduacan Compressors
Compound		**Molecular weight (g/mol)**	**NHV[1/] (kJ/kg)**	**GWP[2/]**	**% Volume[6/] (% mol)**	**% Volume[6/] (% mol)**
CO_2	Carbon dioxide[3/]	44.01	0	1	1.218	2.916
H_2S	Hydrogen sulfide[4/]	34.00	17,397	-40	0.616	1.570
N_2	Nitrogen	28.01	0	0	21.606	24.698
CH_4	Methane[3/]	16.04	50,000	28	56.045	39.218
C_2H_6	Ethane[5/]	30.07	47,208	10	11.731	14.600
C_3H_8	Propane[5/]	44.10	46,400	10	5.640	9.981
C_4H_{10}	Butane[5/]	58.12	45,300	7	1.193	4.986
C_5H_{12}	Pentane[3/]	72.00	45,400	5	0.889	1.651
C_6H_{14}	Hexane[3/]	86.17	44,140	3.06	1.062	0.381

1/ NHV = Net Heating Value

2/ GWP = Global Warming Potential. GWP considered values are for a 100-year period based on IPCC's public information

3/ GWP data from (Intergovernmental Panel on Climate Change, IPCC. 2015)

4/ GWP data from (Jo Gwanggon et. al, 2015)

5/ GWP data from: (Lifetimes, direct and indirect radiative forcing, and global warming potentials of ethane (C2H6), propane (C3H8), and butane (C4H10), 2018)

6/ data from (Cid-Vázquez & Rodríguez-Tovar, 2013)

Source: Own work

Based on publications by Ismail (Saheed Ismail & Ezaina Umukoro, 2014) and Umukoro (Ezaina Umukoro & Saheed Ismail, 2017), the alkane gas mixture of hydrocarbons to be flared, can be represented in the form of C_nH_{2n+2} and calculated through **Equations 1** and **2** for the species in the gas flow stream to be flared. Hence the hydrocarbon gas compositions shown in **Table 1**, can be represented as $\boldsymbol{C_{1.121}H_{3.772}}$. for Samaria II Compressors and $\boldsymbol{C_{1.288}H_{3.993}}$ for Cunduacan Compressors.

$$C_n = \beta_1 C_1 + \beta_2 C_2 + \cdots + \beta_k C_i \tag{1}$$

$$H_{2n+2} = \beta_1 H_1 + \beta_2 H_2 + \cdots + \beta_k H_j \tag{2}$$

Where:
C_n = Individual constituent of the carbon compounds
H_{2n+2} = Individual constituent of the hydrogen compounds
k = number of alkane species in the flow stream
β_k = molar/volume composition by percentage of the k-th C_iH_j specie

The process parameters considered for the OFF and EGF calculations regarding the case studies are similar for both PEMEX facilities: ***Samaria II Compressors*** (Cid-Vazquez & Rodriguez-Tovar, 2013) and

Cunduacan Compressors (PEMEX Exploración y Producción, 2010). Hence, for purposes of this stage the process temperature (T) of the fluids sent out to the flare system, is considered to be 311 K while differential pressure (ΔP)is considered to be 0.34 atm. Normalized (N) conditions are met at P = 1 atm, and T = 273k, whereas Standard (S) conditions are met at P = 0.9678 atm, and T = 293 K.

2.2 Stage 2. OFF and EGF calculations, HAZOP study and consequences analysis

Usually, the gas mixture to be flared is represented by its molecular weight used to calculate the heat released during the combustion. The amount of the combustion products can be estimated given the CE of flare technologies for feasible scenarios such as a) when complete combustion is achieved, and b) when the unburned hydrocarbons are released to the atmosphere due to incomplete combustion.

2.2.1 Volume and mass calculations

As this study is intended for gases to be flared, the general equation for ideal gases shown in **Equation 3** is often used considering the process conditions available at the intake of the flare system.

$$m = PV(MW)/(RT) \quad (3)$$

Where:

m = Mass of the specie in the flow stream to be flared in a time basis
P = Pressure of the flow stream
V = Volume of the specie in the flow stream to be flared in a time basis
T = Temperature of the flow stream
MW = Molecular Weight of the species present in the flow stream to be flared
R = Universal ideal gas constant

Based on equation (3) according to the data displayed in **Table 1 and Table 2**, estimations in a daily basis for the mass flow rate, heat release and tCO_2e emissions can be obtained as per equations 3, 4, and 5 along with the Global Warming Potential (GWP) values as shown in **Table 1**. Further discussion about GWP is presented in **Section 2.4.2**.

$$m_a = \sum_{j=1}^{n} 365 m_j \quad (4)$$

$$m_{CO_2e} = \sum_{j=1}^{n} m_{a_j} GWP_j \quad (5)$$

Where:
m_a = Annual mass flow of the total species in the gas flow rate (flow rate is given in m^3 per day)
m_j = Mass of the *j*-th compound in the gas flow stream
m_{aj} = Annual mass of the *j*-th compound in the gas flow stream
GWP_j = Global Warming Potential of the *j*-th compound in the flow stream
m_{CO_2e}= Annual gas flow stream as CO_2e mass
n = number of species in the flow stream

Table 2 OFF and EGF key parameters for calculations

	Samaria II Compressors						Cunduacan Compressors					
Compound	**Volume (Nm^3/d)**	**Partial molar mass (g/mol)**	**% mass**	**Heat release (kW)**	**Mass (t/d)**	**$CO_2e^{1/}$ (t/d)**	**Volume (Nm^3/d)**	**Partial molar mass (g/mol)**	**% mass**	**Heat release (kW)**	**Mass (t/d)**	**$CO_2e^{1/}$ (t/d)**
CO_2	41,144	0.536	2.20	0	81	81	74,657	1.283	4.50	0	147	147
H_2S	20,800	0.209	0.90	6,356	32	-1,263	40,207	0.534	1.90	12,287	61	-2441
N_2	729,770	6.052	25.20	0	913	0	632,338	6.919	24.50	0	791	0
CH_4	1,893,023	8.992	37.40	870,897	1,356	37,962	1,004,119	6.292	22.30	416,173	719	20136
C_2H_6	396,247	3.528	14.70	319,501	532	5,319	373,801	4.39	15.50	274,155	502	5018
C_3H_8	190,502	2.487	10.30	218,748	375	3,750	255,547	4.401	15.60	270,149	503	5030
C_4H_{10}	40,306	0.694	2.90	59,427	105	732	127,648	2.898	10.30	173,637	331	2318
C_5H_{12}	30,021	0.64	2.70	54,275	96	482	42,274	1.189	4.20	71,394	136	679
C_6H_{14}	35,878	0.915	3.80	70,505	138	422	9,742	0.328	1.20	19,145	37	115

1/ Calculations based on GWP values for a 100-years period

Source: Own work based on data from (PEMEX Exploración y Producción (PEP), 2006)

Based on **Table 2, Table 3** shows relevant parameters calculated for the gas mixtures sent out to the flares under assessment. Worth mentioning that these estimations were considered for the maximum gas flow rates addressed to the flare systems and could be considered as the upper boundaries. However, in real operating conditions these figures might be less or different based upon the operator's criteria and procedures.

Table 3 Calculated process parameters

Parameter	**Unit**	**Samaria II Compressors**	**Cunduacan Compressors**
Gas mixture composition		$C_{1.121}H_{3.772}$	$C_{1.288}H_{3.993}$
Molecular weight	g/mol	24.053	28.234
Daily volumetric gas flow$^{1/}$	NMm^3	3.38	2.56
Daily mass gas flow$^{1/}$	kt	3.63	3.23
Annual mass gas flow$^{1/}$	Mt	1.33	1.18
Weighted average heating value	kJ/kg	34,758	33,119
Combustion net heat release (thermal power)	GW	1.60	1.24
Annual gas flow as pollutant emissions	$MtCO_2e$	17.38	11.35

1/ Estimations are considering: Normal conditions (N), P = 1 atm @ 273K; Standard conditions (S), P = 0.9678 atm @ 293k

Source: Own work

2.2.2 Estimated key parameters

It is assumed that the gas mixture to be flared does not contain solids or liquid carryover, as the flare to be assessed is the last stage in the process before destroying the unwanted gas stream of the facility. Additionally, combustion occurs stoichiometrically and adiabatically, the compounds in the gas mixture do not react with each other when combustion occurs. There are additional considerations and assumptions deemed necessary in this research work but summarized in **Table 4** for the case studies assessed herein.

Table 4. Summary of main considerations and assumptions

No.	Concept
1	Combustion is carried out under stoichiometric conditions.
2	Combustion is carried out under standard conditions when applicable (1 kg/cm^2 @ 20°C).
3	The compounds are chemically pure, do not react with each other and oxidation is total in the combustion.
4	The supply of gases to the burner is in laminar flow in stable condition and in a uniform pressure condition.
5	Combustion is carried out under adiabatic conditions.
6	In the open flame flares (OFFs), the heat and noise produced in combustion are released radially spherically with a focus on the combustion nozzle.
7	Combustion presumes an axial symmetry where chemical reactions occur instantaneously.
8	Combustion assumes as neglectable the actions of diffusion, heat conduction, and viscosity in the direction of the axial axis (x) through which the flame propagates.
9	In the modeling carried out of combustion reactions, efficiency values (η) of 50% to 99.9% are considered viable while excess/defect air (δ) is considered viable in values of 1.30 to 0.90. However, for simplicity the value of excess/defect air is fixed to 1.
10	The length of the flame product of combustion can be reduced by installing several nozzles that perform the same combustion process all of them together.
11	When flaring a gas flow stream, the center of the flame is allocated at one third (1/3) of the flame length.
12	The length and shape of a flame do not change by the action of wind, but the inclination of the flame in an angle (θ) measured from to the vertical axis.
13	The heat released by open flame flares can be contained in enclosed ground flares when the combustion is performed instead into EGF

Source: Own work

The key parameters for designing or sizing an OFF are the combustion net heat release (thermal power), the diameter and height of the flare stack (and the flare tip), the thermal safety radius (R_{Th}), and the thermal safety area (also referred to as the flaring area). **Figure 6** shows a simplified graphical representation of the said key parameters of a non-assisted OFF. These key parameters can be calculated through equations 6 to 14 (Banerjee, Cheremisinoff, & Cheremisinoff, 1985) (Straitz III J. F., 1994).

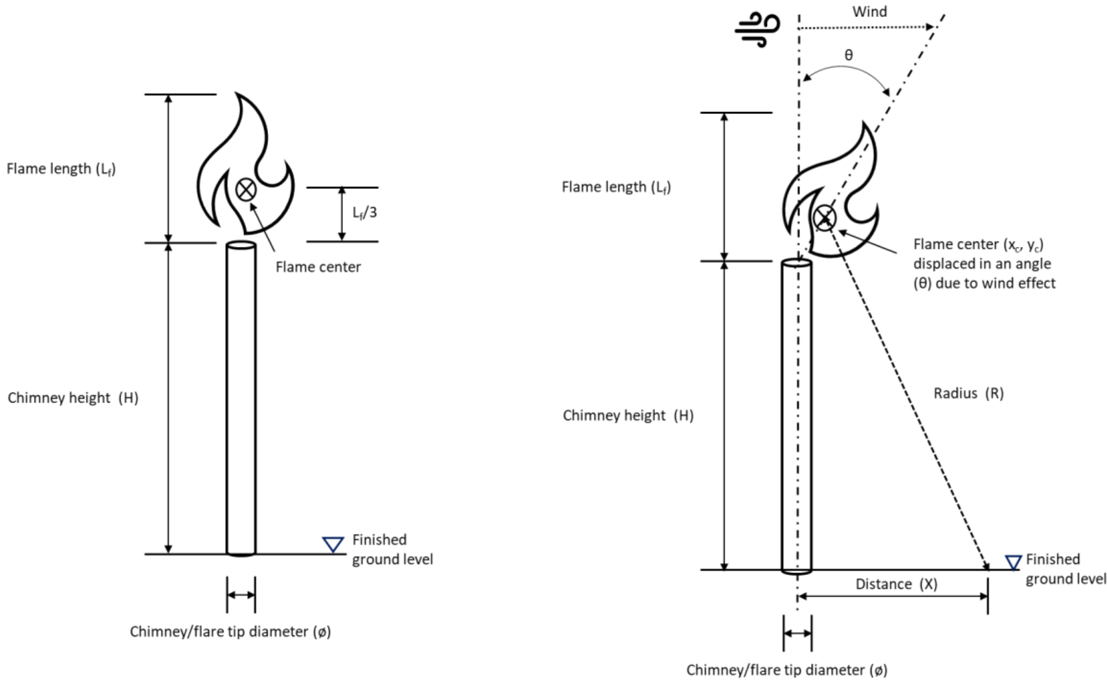

Fig. 6. Simplified diagram of an open flame flare
Source: Own work

$$D^2 = (m/1370)(T/MW)^{1/2}(4/\pi/f_{des}) \qquad (6)$$

Where:

D = Diameter or the flare stack = OFF flare diameter = Also referred as ø (m)
m = Mass of the flow stream (kg/s)
T = Temperature of the flow stream (K)
MW = Molecular Weight of the species present in the flow stream to be flared (g/mol)
f_{des} = Design factor (dimensionless factor). f_{des} = 0.5 on transitory conditions; f_{des} = 0.2 on steady operating conditions

$$L_f = 10D(\Delta P/55)^{1/2} \qquad (7)$$

$$V_{exit} \approx 168(\Delta P/1400)^{1/2} \qquad (8)$$

$$\theta = \tan^{-1}(V_{wind}/V_{exit}) \qquad (9)$$

$$x_c = L_f/(3Sin\,\theta) \qquad (10)$$

$$y_c = L_f/(3Cos\theta) \qquad (11)$$

Where:

L_f = Flame length

D = Flare diameter
ΔP = Pressure drop
V_{exit} = Velocity of the flow stream at the exit of the flare
θ = Inclination angle caused by wind
V_{wind} = Wind velocity at the exit of the flare
V_{exit} = Flow stream velocity at the exit of the flare stack at the end of the flare tip
x_c = Horizontal axis center flame coordinate
y_c = Vertical axis center flame coordinate

$$R_{Th} = ((X - x_c)^2 + (H + y_c)^2)^{\frac{1}{2}} \quad (12)$$
$$H = R_{Th} - y_c = R_{Th} - L_f/(3Cos\theta) \quad (13)$$

Where:
R_{Th}= Thermal safety radius at distance X and height H, considering the coordinates of the flame center.

H = Height of the flare, considering the safety radius (R_{Th}) and the flame center coordinates or the flame length (L_f) and the wind-caused inclination angle (θ).

The height of the OFFs and the thermal radiation intensity at different locations around the flare must be calculated to avoid dangerous situations where personnel, equipment, facility, surroundings, and ecosystem would be exposed to high levels of heat. When the OFF thermal radiation is assumed as a spherical contour, then equation 14 is applicable (Straitz III J. F., 1994).

$$I(r) = \varphi\ NHV\ \varepsilon/4\,\pi\,(r - r_0)^2 \quad (14)$$

where:
$I(r)$= Radiation intensity at point r, (kW/m^2)
φ = Mass flow rate, (kg/s)
NHV= Net Heating Value of the flare gas, (kJ/kg)
ε= Emissivity factor
$(r - r_0)$=R =Radius; distance from the point r to the flame center, (m)
r_0 = Coordinates of the flame center (m)

The emissivity factor (ε) represents a fraction of the heat radiated by the flame. Hence, emissivity depends on the type of compounds to be flared. Based on **Equation 14**, the thermal safety radius (R_{Th}), thus the area of OFFs can be estimated at a given radiation intensity (I). Different regulations call for defining the thermal safety radius when the radiation intensity is fixed at 4.732 kW/m^2 (American Petroleum Institute, 2020) (Petróleos Mexicanos, 2011). **Figure 7** depicts a simplified graphical representation of the heat-radiation exposition contours for OFFs at different levels of I.

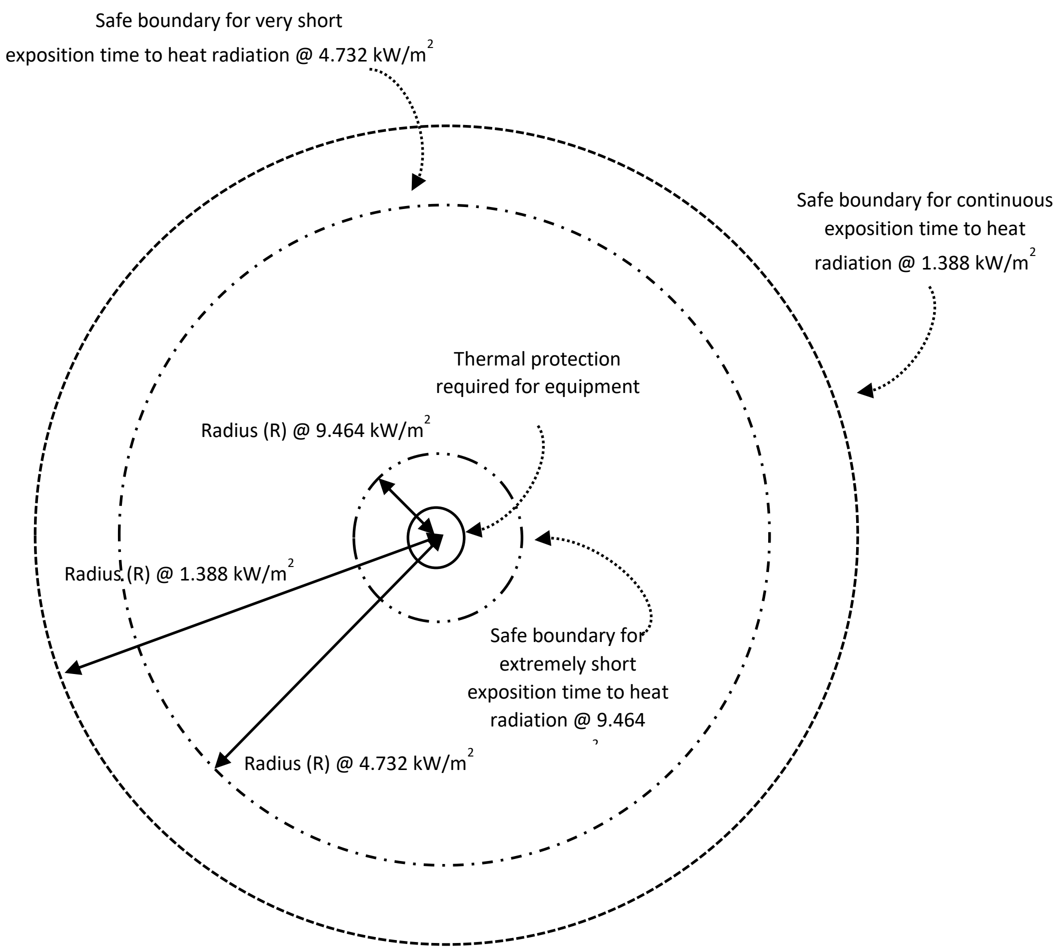

Fig. 7. Simplified heat-radiation exposition contours at different levels of intensity (I)
Source: Own work

The Net Heat Release (NHR) during the combustion of the species present in the flow stream is calculated using **Equation 15.** The volume of the EGF's combustion chamber is defined by **Equation 16**, as per the NHR attained during the previous Stage.

$$NHR = \sum_{j=1}^{n} m_j HV_j \quad (15)$$

Where:

NHR = Net Heat Release
m_j = Mass of the *j*-th specie in the flow stream to be flared
HV_j = Heating value of *j*-th specie in the flow stream to be flared
n = Number of species in the flow stream

$$V_{EGF} = NHR/V_{HRF} \quad (16)$$

Where:

V_{EGF} = Volume of the EGF's combustion chamber as per heat released during combustion of the flow stream

NHR = Net Heat Release

V_{HRF} = Volumetric heat release factor (***206.995 ≤ V_{HRF} ≤ 310.492 kW/m³*** (United Nations. Framework Convention on Climate Change, 2019))

Our assessment is based on the stoichiometric reaction models when flaring a gas mixture of alkane hydrocarbons (in the form of C_nH_{2n+2}) along with CO_2, H_2S, and N_2, mainly from upstream applications. The criteria developed through this assessment may also be applied to refineries and petrochemicals.

Worth to mention that OFF's key parameters were calculated including and focusing in the heat release, then an equivalent EGF is proposed for accomplishing the same flaring task. The technical OFF and EGF estimated parameters for the case studies are shown in **Table 5**. There are different calculation factors available in the technical literature from the American Petroleum Institute (API) (American Petroleum Institute, 2020), the Intergovernmental Panel on Climate Change (IPCC) (United Nations. Framework Convention on Climate Change, 2019), and other sources, based on the heat released during the OFF combustion used for then sizing the EGF's combustion chamber. EGF's insulated combustion chamber designs must be adequate to contain the volumetric heat released during the burning of the gas mixture. Those designs are a function of factors such as the number of internal burners, the size, and the design of the combustion chamber (American Petroleum Institute, 2017). For the purposes of this paper, V_{HRF} = 310.492 kW/m^3 (American Petroleum Institute, 2020) is employed in the volume calculations for a thermally insulated cylindrical combustion chamber (American Petroleum Institute, 2017).

Table 5 shows that the required thermal safety area for Samaria II Compressors' and Cunduacan Compressors' EGF are respectively only 1.3% and 1.4% of the thermal safety area required by the OFFs for an equivalent capacity of the gas flaring process. These reductions in the area are due to deploying internally insulated EGFs instead of OFFs, while releasing valuable pieces of land within the facility which previously were dedicated solely for flaring and now can be used for other applications or equipment. Worth mentioning that most of the Mexican facilities currently are surrounded by different kind of settlements and cannot grow any long in any direction. Hence, recovering some space in the facility for making it available for further uses within the property, including expansion of the capabilities of existing processes, has an intrinsic cost of opportunity that stakeholders could be interested in. Additionally, all aspects related to the Emergency Shutdown System (ESD) installed to protect the entire facility become more complex when a larger thermal safety area is required. Thus, the smaller the flaring area is the better from the ESD standpoint. Also, as can be noted in **Table 5** that the Samaria II Compressors' OFF is 1.8 m taller than the EGF whereas the Cunduacan Compressors' OFF is 0.8 m taller than the EGF, allowing in both cases similar dispersion of the combustion gases. The calculations shown in **Table 5** consider the worst-case scenario, where results are obtained when required through the Low Heating Value (LHV) of the selected compounds and the maximum flow streams.

Table 5. OFF vs. EGF case studies technical assessment

Parameter	Unit	Samaria II Compressors		Cunduacan Compressors	
		OFF	EGF4/	OFF	EGF4/
Diameter1/ (ø):	m	0.524	13.48	0.475	12.7
Height2/ (H):	m	35.2	33.4	32.5	31.7
Safety3/ radius (R_{Th}):	m	58.6	N/A5	54.0	N/A5/
Thermal safety area:	m^2	10,792	141	9,149	126

1/ Stack diameter for OFF; Combustion chamber diameter for EGF

2/ Stack height for OFF; Combustion chamber height for EGF

3/ Thermal safety radius (R_{Th}) for OFF calculated with a fixed radiation intensity = 4.732 kW/m^2 and emissivity = 0.14, according to PEMEX & API regulations Diameter of the combustion chamber for EGF, thermally insulated

4/ For EGFs the ratio Height/Diameter was supposed to be 2.5

5/ EGFs considered to be internally designed with proper thermal insulation in the combustion chamber, hence this concept is not applicable (N/A)

Source: Own work

For validating the results attained by our methodology, a comparison was performed between the results we obtained for the OFF and the existing equipment on-site for the case studies as per PEMEX's publicly available data. The results are shown in **Table 6**.

Table 6. Validation of case studies results by comparing calculated OFF vs OFF on-site values

Parameter	Unit	Samaria II Compressors OFF			Cunduacan Compressors OFF		
		Calculated	Reported on-site	Calculated vs. On-site ratio	Calculated	Reported on-site	Calculated vs. On-site ratio
Gas flow rate (φ):	Mm^3/d	3.4	3.4	1.00	2.83	2.83	1.00
Diameter1/ (ø):	m	0.52	0.51	1.02	0.475	0.40	1.19
Height2/ (H):	m	35.2	33.6	1.04	32.	32.5	1.00

1/ Stack diameter for OFF

2/ Stack height for OFF

Source: Own work

As PEMEX has not yet installed any EGF on-site, for validating our methodology we used the data of an existing EGF built down in Siberia, such as the molecular weight of the mixture, the volumetric and mass flow rates, the average heat release along with the physical diameter and height of its combustion chamber. These data were used as inputs of our methodology in two steps, the first one was to calculate the volume and the height of the combustion chamber considering a V_{HRF} of 310 kW/m^3 and the physical diameter of the EGF. The calculated height was found to be 2.8 m shorter than the physical reported value. The second step was fixing the diameter and height to the physical reported dimensions of the EGF combustion chamber, for finding out that the required V_{HRF} was 286.4 kW/m^3. In both cases the V_{HRF} values are in the acceptable range defined in **Equation 16.** **Table 7** shows the commented results.

Table 7. Validation of the methodology by comparing the physical and calculated values for the Siberia's EGF

Physical Parameter	Unit	Value
Molecular Weight (MW):	g/mol	28
Volumetric flow (φ):	Mm^3/d	3.11
Mass flow	**t/h**	**105**
Heat release:	MW	1,348
Physical Diameter (D):	m	12.80
Physical Height (H):	m	36.57
Physical combustion chamber volume:	**m^3**	**4,707**
First step		
Volumetric heat release factor V_{HRF}[1/] (1st estimation by fixing V_{HRF})	**kW/m^3**	**310**
Calculated combustion chamber volume:	m^3	4,349
Physical Diameter (D):	m	12.80
Calculated Height (H):	m	33.79
Ratio $V_{calculated}/V_{physical}$ =		0.924
Second step		
Volumetric heat release factor V_{HRF}[1/] (2nd estimation by fixing D&H)	kW/m^3	286.40
Physical Diameter (D):	m	12.80
Physical Height (H):	m	36.57
Physical combustion chamber volume:	m^3	4,707
Ratio $V_{calculated}/V_{physical}$ =		1.000

1/ V_{HRF} = Volumetric heat release factor (206.995 ≤ VHRF ≤ 310.492 kW/m3 (United Nations. Framework Convention on Climate Change, 2019))

Source: Own work

It is well known that EGFs will perform well compared to elevated flares due to the reduced effect of crosswind, less heat loss, and controlled operating conditions. Also, since the combustion in an EGF takes place at the bottom of the combustion chamber, temperatures of combustion gases generated in EGF are cooler than in OFFs causing less impact to the environment. Technical literature suggests that process equipment can be located 10 to 25 m from the EGF (Energy Now Media/Westech, 2021), due to the insulated wall that avoids heat dissipation at ground level.

When OFFs require predictive or corrective repairs, it is not a quick and easy task, as it is necessary to shut down the OFF and sometimes even the entire facility during the maintenance, which impacts the productivity of the facility. EGF parts and components, i.e., control panels, pilots, instruments, auxiliary controls, and staging systems, are always accessible due to its thermal insulation and available all the time at ground level for the technicians, even while the flare is in operation. This capability allows the end-users to perform preventive and corrective maintenance, inspections, and repairs, while the flare is online, as well as real-time monitoring of the EGF performance and emissions. Thus, repairs and maintenance in EGFs could be performed in a much shorter time than in OFFs.

2.2.3 Simplified HAZOP study and Consequence analysis through PHAST simulations

The compounds present in a gas mixture to be flared may cause fires, explosions, or toxic clouds if not managed with care. Heat radiation, explosion hazards, and liquid carryover must be considered in the safety analysis of hydrocarbon facilities (Straitz III J. F., 1994) (Shore, 1996). Usually, flares are included in the risk analysis (RA) methodologies regarding the safety of hydrocarbon facilities (Mehdi, Aleghafouri, & Alireza, 2014). As a part of the RA required in hydrocarbon facilities a Hazard and Operability study (HAZOP) must be performed, which is a systematic way to identify possible hazards in a work process (DuraLabel, 2023). Usually, a HAZOP is a very complex study involving most of the hazards affecting the operability of critical components within the facility and its safety. Nevertheless, for grounding ideas, **Figure 8** shows a simplified block diagram of a non-assisted flare system (OFF/EGF). Whereas based on the troubleshooting of ignition systems provided by the API-STD-537 (American Petroleum Institute, 2017), a simplified HAZOP study for OFFs and EGFs is presented in **Table 8,** as most of the time a failure in the flare system implies a plant shut-down. Examples of hazards due to OFF and EGF flares operating under risk conditions are shown in **Figure 9**.

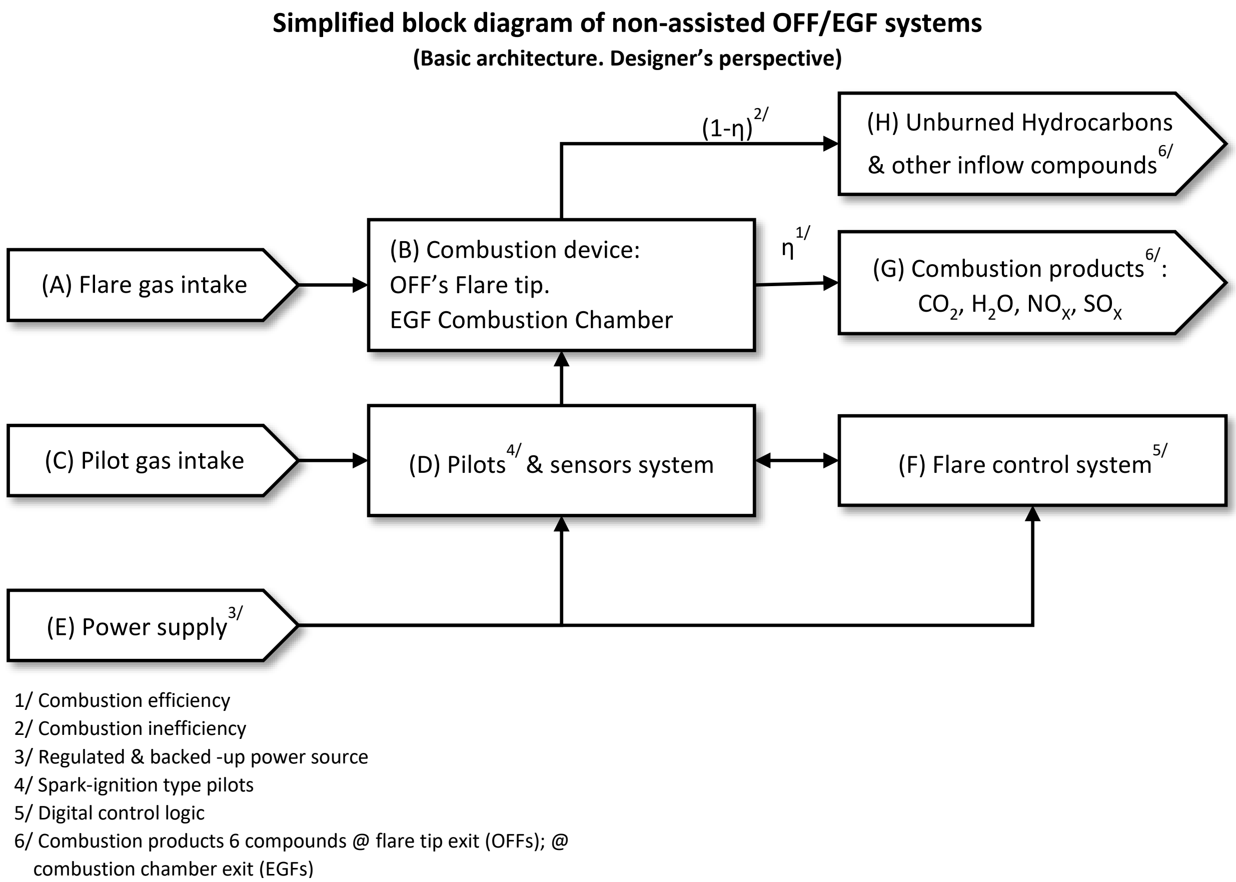

Fig. 8. Simplified flare system architecture
Source: Own work

Table 8. Simplified OFF/EGF HAZOP study.

Item	Element	Potential hazards	Possible consequences	Proposed risk mitigation action
A	Flare gas intake	Over/under pressure; liquids/solids carry over; fluid different from specified gas mixture	Malfunction of the flare system. Corrosion, cracks, leaks. Flame quenching. Flame flash back (when sudden under pressure occurs)	Restore original (nominal) process conditions and settings. Return to design gas mixture. Refer to technology supplier manual for resetting to design conditions
B	Combustion device: OFF's flare tip/EGF Combustion chamber	Flare design inadequate to the application case. Over/under pressure, liquids/solids carry over, fluids different from specified gas mixture, gas leaks, gas clouds. Flame quenching. Noise & heat radiation. Maintenance lack	Malfunction of the flare system. Corrosion, cracks, leaks. Flame quenching. Flame flash back (when sudden under pressure occurs), and internal firing. Flash fires, explosions (in OFFs). Light, noise and heat release on site in the facility and surroundings	Restore original (nominal) process conditions and settings. Return to design gas mixture. Refer to technology supplier manual for resetting to design conditions. Prevent explosive mixture formation. Provide proper maintenance. Avoid corrosion and check proper electrical grounding
C	Pilot gas intake	Over/under pressure, liquids/solids carry over; fluids different from specified gas mixture; gas leaks, gas clouds. Maintenance lack	Malfunction of the flare system. Corrosion, cracks, leaks. Flame quenching. Flame flash back (when sudden under pressure occurs), and internal firing. Flash fires, explosions (in OFFs)	Restore original (nominal) process conditions and settings. Return to design gas mixture. Refer to technology supplier manual for resetting to design conditions. Prevent explosive mixture formation. Verify correct wiring, adequate thermal and electric insulation. Provide proper maintenance. Avoid corrosion and check proper electrical grounding
D	Pilots and sensor systems	Over/under pressure, liquids/solids carry over; fluids different from specified gas mixture; gas leaks, gas clouds. Maintenance lack	Malfunction of the flare system. Corrosion, cracks, leaks. Flame quenching. Flame flash back (when sudden under pressure occurs), and internal firing. Flash fires, explosions (in OFFs)	Restore original (nominal) process conditions and settings. Return to design gas mixture. Refer to technology supplier manual for resetting to design conditions. Prevent explosive mixture formation. Provide proper maintenance. Avoid corrosion and check proper electrical wiring and grounding
E	Power supply	Power failure.	Malfunction of the flare system. Ignition failure	Prevent explosive mixture formation. Provide proper maintenance. Avoid corrosion and check proper electrical connections, wiring and grounding
F	Flare control system	Power failure. Digital control logic failure	Malfunction of the flare system. Flame quenching. Flame flash back (when sudden under pressure occurs), and internal firing. Flash fires, explosions (in OFFs)	Prevent explosive mixture formation. Provide proper maintenance. Avoid corrosion and check proper electrical connections and grounding
G	Combustion products (@ flare exit): CO_2, H_2O, NO_X, SO_X	Inadequate dispersion of hot pollutants gases.	High concentrations of toxic and hazardous compounds around the flare and its surroundings	Provide adequate conditions for hazardous combustion products dispersion.
H	Non combusted compounds (@ flare exit): Hydrocarbons, CO_2, N_2, H_2S	Inadequate dispersion of unburned hydrocarbons and hazardous pollutant compounds in the gas mixture be destroyed by the flare.	High concentrations of toxic and hazardous compounds around the flare stack (OFFs) and its surroundings. Gas clouds, flash fires and explosions (in OFFs)	Provide adequate conditions for hazardous combustion products and non-combusted compounds dispersion.

Source: Own work

A) OFFs operating under risk conditions.
Source: Courtesy pictures by ESISA® & NAO, Inc

B) EGFs operating under risk conditions
Source: Courtesy pictures by NAO, Inc

Fig. 9. Examples of flares in operation in hazardous conditions

The Consequence Analysis (CA) as part of the RA, provides a quantitative assessment of the spatial and temporal evolution of events involving hazardous substances and the possible effects if an incident takes place (Wu, Wei, Gao, Han, & Weijian, 2019) (Agencia de Seguridad, Energía y Ambiente, 2020) (Wu, Kong, Wei, Gao, & Xiong, 2020). The CA methods are used to estimate the nature and extent of the damage due to a loss of control of those substances; this is identified as an incident caused by an upset condition. Startups and scheduled maintenance actions are not considered to be incidents as they correspond to calculated and programmed risk situations (Secretaría del Trabajo y Previsión Social (STPS), 2021) (Puskar, 2014). The CA can be carried out using different tools and methods, often the Process Hazard Analysis Software Tool (PHAST) developed by Det Norske Veritas (DNV) is used. This tool simulates an incident and assesses the potential consequences that may happen due to the pre-programmed upset condition (Wu, Wei, Gao, Han, & Weijian, 2019) (Agencia de Seguridad, Energía y Ambiente, 2020) (Wu, Kong, Wei, Gao, & Xiong, 2020). The CA should be performed prior to deciding which flare option is more suitable for the application under analysis.

Bearing in mind focusing on the larger case, PHAST simulations were performed for the CA just for the Samaria II Compressors case study considering failure conditions such as a leak occurring in the OFF and EGF. The incidents on both flares, considered a detection and response time of 120 seconds for the safety control logic and capabilities of each flare. Calculations were made accordingly about the safe distance that should prevail for avoiding consequences in case of incidents such as gas leaks, explosions, or flash fires (Wu, Wei, Gao, Han, & Weijian, 2019) (Wu, Kong, Wei, Gao, & Xiong, 2020).

OFF simulated failure consists of the sudden appearance of a 5 cm hole in the inflow pipeline at the bottom of the flare, 4m above ground level. For simplicity in the simulation, this height was fixed and considered to clear the potential dimensions of complementary components such as water seals, slug catchers, knock-out drums, or pipeline racks. The selected OFF is assumed to have a single flare tip able to manage the high and low pressures of the flow stream.

EGF simulated failure scenarios for the case study were assumed to occur during the regular operation in any of its 60 burner tips (47 for high pressure and 13 for low pressure) occurring at a burner height of 1.8 m. The incident modeled is due to a sudden beheading in a 5 cm manifold of an internal burner inside its combustion chamber during the operation of the EGF. **Table 9** shows the results from the PHAST simulations at different wind speeds, i.e., 1.5, 5.5, and 33.33 m/s whereas the atmospheric stability considerations were F, C or D, and D Pasquil grades respectively.

Table 9. Affectation horizontal distances (in m) for the gas leak simulated incidents

				Wind speed (m/s)/Atmospheric stability (Pasquil grades)					
Consequence	**Parameter**	**Unit**	**Value**	**1.5/F**	**5.5C/D**	**33.33/D**	**1.5/F**	**5.5C/D**	**33.33/D**
					OFF			**EGF**	
Gas cloud	Fuel concentration	ppm	22,485.5	13.5	11.5	7.8	2.77	2.44	1.74
Flash fire envelope	Fuel concentration	ppm	22,485.5	13.5	11.5	7.8	2.77	2.44	1.74
Explosion	Overpressure	atm	0.5	19.0	18.3	15.5	NA[1/]	NA[1/]	NA[1/]

1/ NA = Not Applicable, as explosion conditions were not reached

Source: Own work

Considering the data of **Table 9**, in case of a leak occurring in the OFF, having the full load of the sour gas escaping at 4 m above ground. Then, a gas cloud will be formed and tend to expand horizontally with a contour that can be seen in **Figure 10**. Anything present in a distance between 7.8 to 19 m could be affected either by a sour gas cloud, a flash fire, or an explosion in the vicinity of the flare's structure and equipment. Whereas the leak occurs in the EGF at 2 m height with a portion of the gas load inside the combustion chamber, then the gas cloud will tend to expand as shown in **Figure 11**, and affectations could occur in a distance between 1.7 and 2.8 m inside the combustion chamber. In both cases, due to the consideration of 120 seconds of the response time of the flare system logic, further damages were avoided to occur at larger distances of the leak.

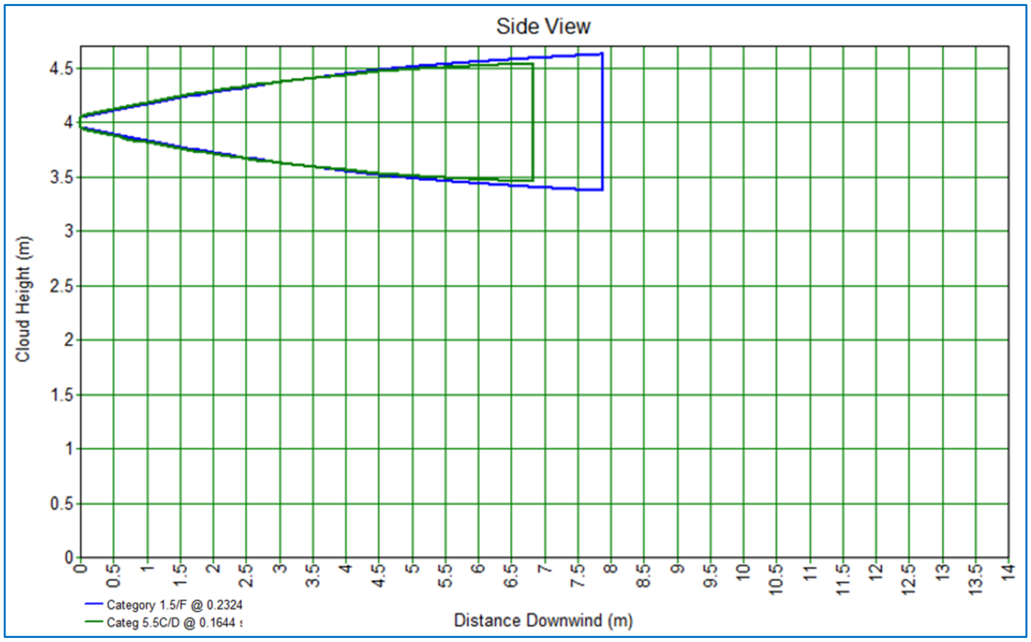

Fig. 10. Side view of the gas cloud leak in the OFF-case study
Source: Own work

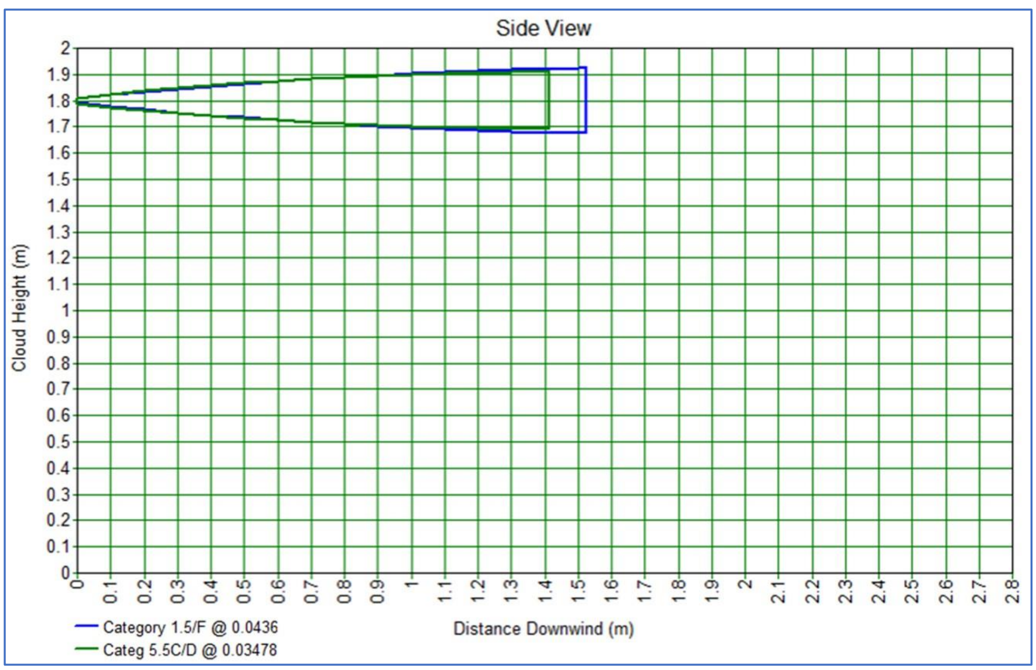

Fig. 11. Side view of the gas cloud leak in the EGF-case study
Source: Own work

The distances provided by PHAST Software are smaller than the thermal safety radius (R_{Th}) of 58.6 m for the OFF as shown in **Tables 5**, and **9**. Hence, the potential affectations due to the simulated incident for the OFF would occur in open areas around the flare within the thermal safety radius. For the EGF, the distances of affectation will be contained within the combustion chamber.

For a better comprehension of some of the concepts listed in **Table 9**, **Figures 12**, and **13** respectively show off-site and on-site views of the case study. Notes and remarks were added according to the said views as per the results obtained in this work.

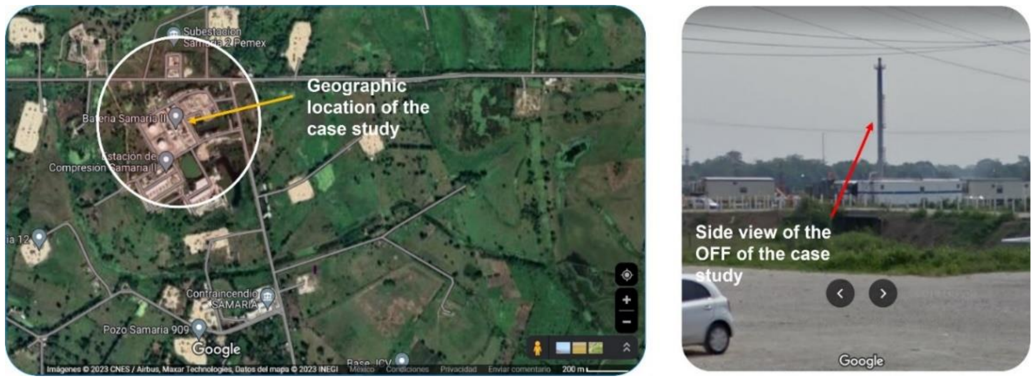

Fig. 12. Off-site view of the case study location
Source: Own work

Fig. 13. On-site view with comments for the OFF and EGF case study
Source: Own work

2.3. Stage 3. Stoichiometric and combustion efficiency considerations

Emissions of climatic forcers such as CO_2 and other air pollutants are strongly sensitive to the CE of flares as discussed in **Sections 2.3.1, 2.3.2, 2.4.1,** and **2.4.2.** The selected flare technology should be able to operate at the specified CE for the ongoing process conditions in the facility, considering that the CE does not remain constant during the entire OLT.

OFFs can withstand high volumetric flow rates at higher velocities and could be safer when compared with EGFs for facilities with storage tanks. However, it has been observed that in Asia there are several hydrocarbon facilities (Refineries, Petrochemicals, LNG stations) with storage tanks that use EGFs with a good safety record (Straitz III & Chua, Enclosed flares: A look inside today's state-of-the-art systems, 1996).

2.3.1 Stoichiometric considerations. Reactions for sour gas combustion

Stoichiometry models are essential tools to the proposed methodology for estimating the combustion products generated in flares. Sour gas reactions issued by Umukoro (Ezaina Umukoro & Saheed Ismail, 2017) are applicable to our stoichiometric analysis for Mexican case studies. To achieve Stage 3 of our Methodology, **Equations 17, and 18** (The John Zink Hamworthy, 2013) shows the typical stoichiometric reaction of alkane hydrocarbons considering the amount of air due to excess/deficit (δ) of air that is associated with combustion processes. **Equation 19** (Martin Leciñena, 2018) depicts the typical stoichiometric reaction when combusting H_2S.

$$C_nH_{2n+2} + \delta\left(n + \frac{2n+2}{4}\right)(O_2 + 3.76N_2) \rightarrow nCO_2 + \left(\frac{2n+2}{2}\right)H_2O + (\delta - 1)\left(x + \frac{2n+2}{4}\right)O_2 + \delta\left(n + \frac{2n+2}{4}\right)3.76N_2 \quad (17)$$

Where:
C_n = Individual constituent of the carbon compounds
H_{2n+2} = Individual constituent of the hydrogen compounds

$$\delta = \frac{\%\,(excess\ or\ deficit\ of\ air)}{100} + 1 \quad (18)$$

Where:
(% excess or deficit of air) is the percentage of air in regard to the required for a stoichiometric combustion

$$H_2S + \frac{3}{2}\,O_2 \rightarrow SO_2 + H_2O \quad (19)$$

Usually, combusting hydrocarbons may result also in releasing into the atmosphere emissions of N_2O due to incomplete combustion processes (Ziyarati, Bahramifar, Baghmisheh, & Younesi, 2019). It is considered that the formation of N_2O is inversely proportional to the concentration of CH_4 (Verma, 2002), which in turn means that the higher contents of CH_4 in the flow mix to be flared, the smaller the N_2O formation occurs during the flaring. The N_2O formation process is almost the same for different temperature profiles but promptly decreases with flame residence time for higher combustion temperatures (Verma, 2002). At high temperatures, N_2O quickly decomposes to 33% O_2 and 67% N_2 (Chen & Li, 2021). Hence the combustion reaction models used in this work do not consider the formation of N_2O during the flaring of the gas mixtures assessed herein as the presence of such combustion product is negligible at the combustion temperatures considered for the case studies as discussed in **Sections 2.4.1**.

Based on the results discussed by Ismail (Saheed Ismail & Ezaina Umukoro, 2014) and Umukoro (Ezaina Umukoro & Saheed Ismail, 2017), for simplicity in our assessment, it is feasible to consider that stoichiometric combustion is occurring when flaring, meaning that no excess or deficit of air is required by the OFF and EGF technologies. Hence, pollutant emission figures can be estimated through the combustion reactions proposed by Umukoro and Ismail. The breakdown of the amounts of the reactants and products is described in **Sections 2.4.1 and 2.4.2**. Depending on the temperature of the combustion reaction of the gas mixture, diverse products will be formed while prevailing in the stoichiometric elementary balance of the combustion.

Whenever flare technologies are acquired, the new equipment performs the flaring at its best CE, usually ranging from 0.999 to 0.95. The higher the CE, the higher the cost of the equipment. The CE reduces from 0.999 to 0.50 (even to 0) (United Nations. Framework Convention on Climate Change, 2019) due to aging or operating the equipment in non-nominal design conditions or insufficient maintenance. Pollutant emissions tend to increase with CE linear degradation as defined in **Sections 2.4.1 and 2.4.2**, causing unburned or reformed hydrocarbon emissions during incomplete combustion.

2.3.2 Combustion efficiency considerations

Although OFFs are commonly used around the world, generally there is limited access to precise data for addressing the issues of their efficiencies, inefficiencies, and emissions (Johnson & Kostiuk, 2002). Hence, as per Stage 3 of our Methodology, combustion efficiency considerations must be assumed as follows. As per laboratory and on-site studies conducted by Strosher in 2000 about flaring hydrocarbons in O&G fields, it was determined that crosswind reduces the CE of OFFs. Decaying from over 0.99 efficiencies to values in the range of 0.62 to 0.88 causing unburned or thermally reformed hydrocarbons to be released into the atmosphere as pollutant emissions (Strosher, 2000). Flow streams with reduced energy density flames, meaning gases with low heating values (LHV), are very susceptible to crosswind effects (Johnson & Kostiuk, 2002) by decreasing the CE (η) or increasing the combustion inefficiency (1-η) of the OFFs. Studies performed by Leahey and Preston in 2001 determined that the CEs in OFFs tend to be sensitive to crosswind speeds and stack exit velocities, as the flame volume and area are also dependent on such parameters (Leahey, Preston, & Strosher, 2001). Based on OFF's design criteria, temperatures (of the flow streams to be flared) and wind loads must be considered to apply simultaneously (American Petroleum Institute, 2017). Wind loads are considered to deflect the flame downwind from its vertical axis while developing a projection of the flame in the ground plane impacting the thermal safety area. As long as the flame is outside the boundary layers of the OFF's structure, the combustion efficiency is independent of the stack height (Johnson & Kostiuk, 2002), and the CE is affected by other factors.

According to the US-EPA, to maintain high combustion efficiency (> 98%) in stoichiometric conditions the fuel value of the flow streams to be flared, should be in excess of 7,500-9,300 kJ/m^3 (Leahey, Preston, & Strosher, 2001). Depending on the composition of the hydrocarbon flow stream to be flared, in regular wind conditions field experiments have determined that flame temperatures ranging from 1,148 K to 1,300 K (Leahey, Preston, & Strosher, 2001) are suitable for high CEs (CE > 0.98) in flare technologies. Combustion efficiency decreases linearly and smokeless performance in air-assisted flares when the air-assist to fuel gas ratio is exceeded beyond its limit (Fawole, Cai, & MacKenzie, 2016) (Shore, 1996) which applies to our case study. Decrements in the combustion efficiency of diffusion flame flares are due to the random and uncontrolled nature of the combustion process (Shore, 1996). Decreasing the CE of flares will result in increasing the noise produced by the flare due to the cavitation created within the flame (Fawole, Cai, & MacKenzie, 2016) along with increases in GHG emissions. The use of supplementary flames in OFFs, such as pilot burners at the base of the main flame, is a major factor in flame stabilization and reducing combustion inefficiency (Shore, 1996). This principle is also applicable to EGFs because these technologies have a large number of burners and pilots within their combustion chamber, enhancing the stabilization and combustion efficiency of the internal flames not being affected by environmental factors such as wind loads.

Due to its implications for OFFs and EGFs, the flame length is a critical parameter that should be carefully estimated as it impacts in different ways the sizing of these two technologies as they are related one each other. Flame efficiencies decrease whenever a single flame size decreases, as long as there are increases in the stoichiometric air-fuel mixes, wind speed, and stack exit velocity. Hence, decrements in the flame size will occur in a significant way, impacting the high CE (Leahey, Preston, & Strosher, 2001). Due to the high effect of crosswind on the CE of OFFs, some researchers consider that elevated OFFs represent the most significant problem for controlling emissions of toxic air pollutants and they encourage the use of flare gas recovery systems, or wind-protected EGFs and THOs (Industry Professionals for Clean Air, My 23, 2005) as those technologies have a better performance than OFFs from the destruction efficiency standpoint.

2.4. Stage 4. OFF and EGF pollutant emissions estimations

2.4.1 Pollutant emissions by stoichiometric calculations for sour gas flaring.

Since the case studies data involves sour gas flaring, the formation of NO, NO_2, and SO_2 depends on the combustion reaction models such as those proposed by Umukoro and Ismail in 2017, whereas N_2O formation can be neglected as per **Section 2.3.1**. The operative performance of gas flares initiates with higher values of CE (represented by η) whenever the equipment is brand new and linearly diminishes in time as discussed in **Section 2.3.2**. Stage 4 of our methodology requires different pollutant emission calculations which start in this section based on **Section 2.3.1**. The formation of CO_2, CO, and SO_2 during flaring occurs at any combustion temperature. Whereas the formation of NO and NO_2 depends on the combustion temperature during the oxidation reactions. In a 30-year period, several emissions calculations were performed for the case studies considering OLTs such as 6, 10, 15, and 30 years corresponding to the proposed OFFs and EGFs. **Table 10** shows for Samaria II Compressors an example on the said calculations and pollutant emissions formation as a function of the inflow composition, CE, combustion reaction models and OLT. Hence, **Figures 14** and **15** show the annual combustion products formation of million tons (Mt) of pollutants generated by OFF and EGF based on their operating lifetime (OLT) respectively for the Samaria II Compressors and Cunduacan Compressors facilities. When developing **Figures 14** and **15**, it was considered that OFF's CE linearly decayed from 0.999 to 0.5 respectively in 6, 10, and 15 years, while EGF's CE linearly decayed from 0.999 to 0.9 in 30 years. It was also considered that whenever the CE reaches the lower limit in the flare's lifetime (η = 0.5), the equipment is cyclically replaced in a 30-year period by a new one, and CE is raised to the higher limit again.

Table 10. Example of annual pollutant formation (t/y) worksheet for Samaria II, as function of OLT, CE and mass flow rates

Combustion temperature	OLT	Non-Combusted	CO_2	CO	SO_2	NO	NO_2	Total non-hydrocarbon pollutants
$\forall T$	6 years	9,509,506	4,482,722	660,146	43,705			5,186,573
$\forall T$	10 years	10,210,687	4,307,957	699,032	42,805			5,049,794
$\forall T$	15years	10,561,278	4,221,510	717,880	42,355			4,981,744
$\forall T$	30-years	2,199,798	6,376,039	209,311	53,087			6,638,437
1200 K ≤ T ≤ 1600 K	6 years OFF	9,509,506	4,482,722	660,146	43,705	949,022		6,135,595
1201 K ≤ T ≤ 1600 K	10 years OFF	10,210,687	4,307,957	699,032	42,805	1,004,925		6,054,718
1202 K ≤ T ≤ 1600 K	15 years OFF	10,561,278	4,221,510	717,880	42,355	1,032,020		6,013,764
1203 K ≤ T ≤ 1600 K	30 years EGF	2,199,798	6,376,039	209,311	53,087	300,905		6,939,342
T > 1600 K	6 years OFF	9,509,506	4,482,722	660,146	43,705	474,511	727,520	6,388,604
T > 1600 K	10 years OFF	10,210,687	4,307,957	699,032	42,805	502,462	770,375	6,322,631
T > 1600 K	15 years OFF	10,561,278	4,221,510	717,880	42,355	516,010	791,146	6,288,900
T > 1600 K	30 years EGF	2,199,798	6,376,039	209,311	53,087	150,452	230,674	7,019,563

Source: Own work

As can be noted in **Figure 14**, for the Samaria II Compressors case study, EGFs annually release into the atmosphere 2.2 Mt of unburned hydrocarbons ($C_{1.121}H_{3.772}$) in comparison to the annual releases of 9.5, 10.2, and 10.6 Mt for OFFs for OLTs of 6, 10, and 15 years respectively. Thus, EGFs release 78% less unburned hydrocarbons than OFFs which is a significant environmental benefit that also could become an interesting economic benefit considering either the carbon credits or reducing carbon taxation as in some States within Mexico. An example is the State of Queretaro, where currently an avoided or compensated ton of CO_2e emissions is worth 25 USD (Secretaría de Desarrollo Sustentable del Estado de Querétaro, 2023). In the Samaria II case study, OFF's releases of unburned hydrocarbons are, on average, 4.6 times the releases of EGFs in a 30-year period whatever the OFF's OLTs would be (6, 10, or 15 years). Regarding Cunduacan Compressors, similar results as discussed above are shown in **Figure 15,** where it can be noticed that EGF annually releases into the atmosphere 1.67 Mt of unburned hydrocarbons ($C_{1.288}H_{3.993}$). Additionally, in both cases EGFs have a lesser formation of CO, SO_2, NO, and NO_2 than OFFs. This is important as all these compounds are criteria pollutants that must be diminished as much as possible when flaring due to their impact on health. However, focusing on NO_2 formation, this is a toxic compound with harmful effects on the lungs of people and animals but also on vegetation. NO_2 is synergetic with SO_2 in the presence of hydrocarbons. NO_2 and SO_2 can interact in the atmosphere to produce nitric acid (HNO_3) becoming precursors of both acid rain and tropospheric O_3 pollution (Tropósfera. Portal temático de contaminación atmosférica., 2011). Hence, diminishing NO_2 and SO_2 formation through deploying EGFs leads to reducing the formation of acid rain as well as tropospheric O_3 pollution. Nevertheless, due to their higher CE, EGFs have a larger CO_2 formation, in Section 4.6 it is discussed how to deal with this issue in the GLW context. Although CO_2 formation is higher in EGFs in a 30-year period, OFFs release a much larger quantity of unburned hydrocarbons which is much worse from GLW and environmental impact standpoints.

Considering the emission reduction commitments by Mexico in the Paris Agreement, the relevant results of this research lead to consider the use of high-efficiency flare technologies such as EGF is a practical, effective mitigation action that Mexico could implement in the short term for fulfilling its intended Nationally Determined Contributions (iNDCs). Additionally, reductions in CO and SO_2 emissions (Bréon, y otros, 2013) as it happens when deploying EGFs, consequently, cause important reductions in BC and particulate matter ($PM_{1,2.5,10}$) and mitigate health impacts. Thus, the results of this research work aim to mitigate climate forcers formation through the deployment of EGFs and OFFs with high CEs, disregarding the use of OFFs with poor CE as those with a maintenance lack as well.

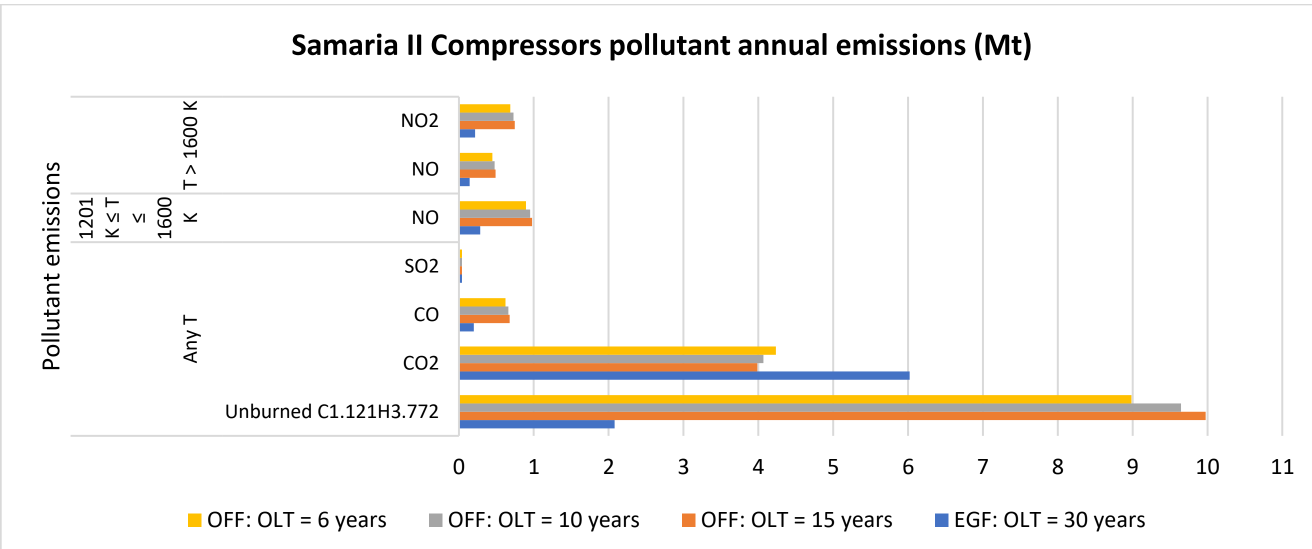

Fig. 14. Samaria II pollutant emissions as a function of OLT and combustion temperature (T)
Source: Own work

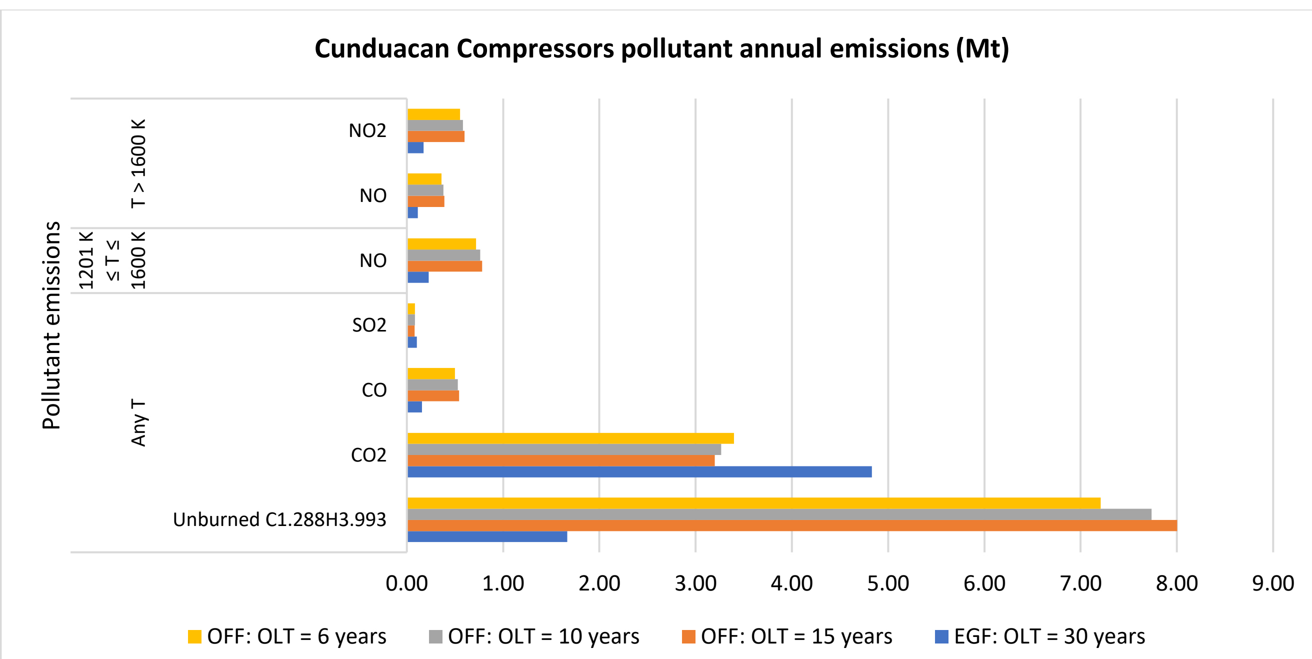

Fig. 15. Cunduacan pollutant emissions as a function of OLT and combustion temperature (T)
Source: Own work

2.4.2 Pollutant emissions by CO_2e calculations due to unburned hydrocarbons

Metrics of pollutant emission through Global Warming Potentials (GWPs) and CO_2e emissions are a widely accepted way to quantify and communicate the contributions of substances to climate change by country, region, sector, or source (Bréon, y otros, 2013). The method for estimating CO_2e emissions consist of multiplying the tons of a substance released into the atmosphere times its GWP as stated in **Equation 5**. Worth mentioning that GWP has been assessed over different fixed time periods, i.e., 20, 100, and 500 years, being the 100-year the most popular since gases have different lifetimes in the atmosphere. However, these specific time horizons should not be considered as having any special scientific significance according to the opinions of researchers of the Intergovernmental Panel on Climate Change (IPCC) released in 2013 (IPCC 2013) (U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University, 2015). The 100-year GWP (GWP_{100}) method has been adopted as a default metric by the United Nations Framework Convention on Climate Change (UNFCCC) (Intergovernmental Panel on Climate Change, IPCC, 2015) (European Union, 2014).

Alkane hydrocarbons are considered to have GWP values less than 150 and zero Ozone Depletion Potential (ODP) (Bahrami, Pourfayaz, & Kasaeian, 2022), and some of the GWP values must be calculated as not all these substances are listed by the IPCC (Jo Gwanggon, y otros, 2015) (Lifetimes, direct and indirect radiative forcing, and global warming potentials of ethane (C2H6), propane (C3H8), and butane (C4H10), 2018). Hence, gas mixture compounds defined in Section 2.2, were found to have different GWP_{100}- values already shown in **Table 1.**

Based on **Section 2.4.1**, **Figures 16** and **17** respectively for Samaria II Compressors and Cunduacan Compressors, show the calculated CO_2e emissions that would be released into the atmosphere in a 30-year period due to the unburned hydrocarbons (respectively $C_{1.121}H_{3.772}$ and $C_{1.288}H_{3.993}$) according to flares' OLT.

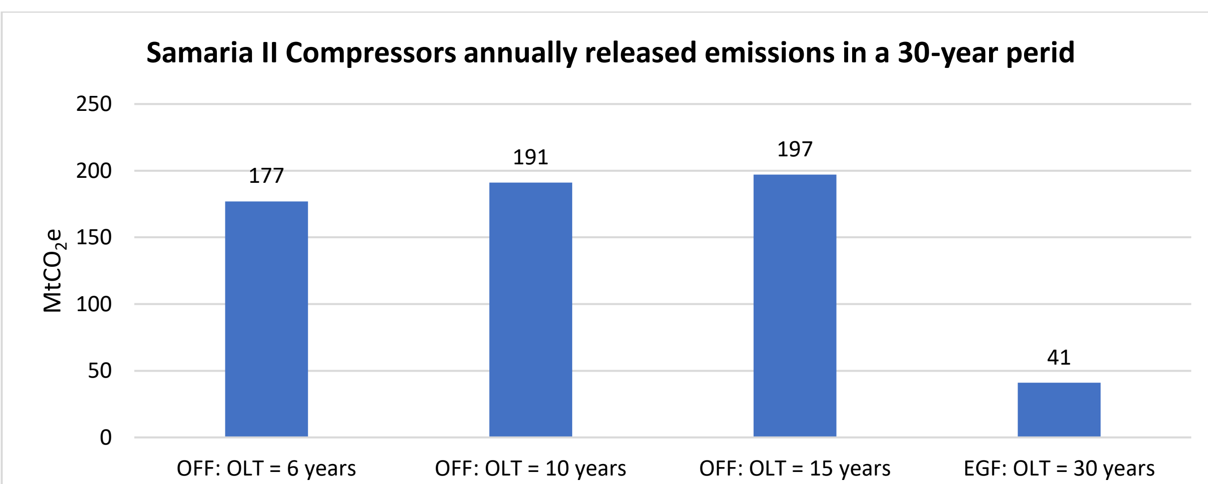

Fig. 16. OFF's vs. EGF's CO_2e pollutant emissions due to unburned $C_{1.121}H_{3.772}$
Source: Own work

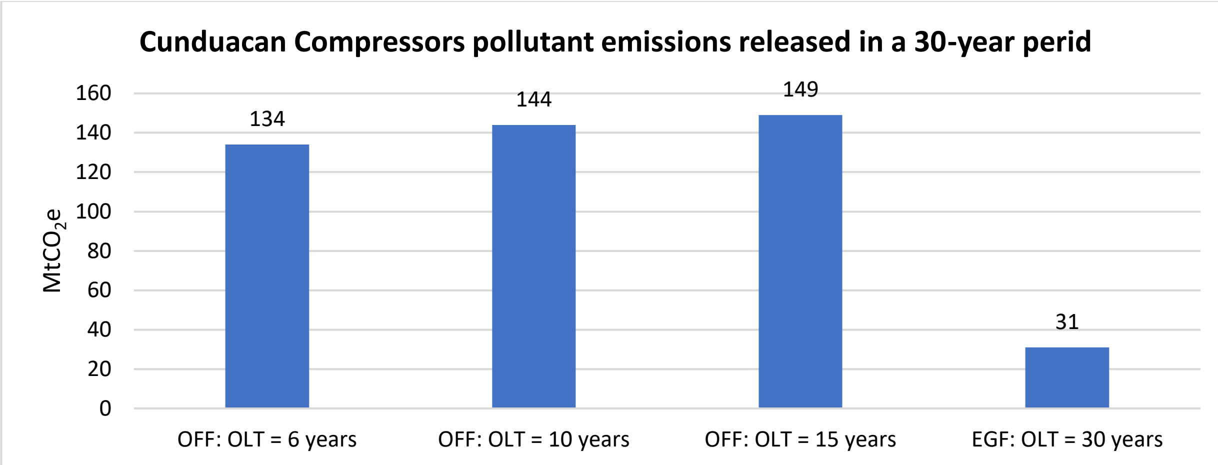

Fig. 17. OFF's vs. EGF's CO_2e pollutant emissions due to unburned $C_{1.288}H_{3.993}$ in 30-year period
Source: Own work

From **Figures 16** and **17**, it can be seen that when the EGF alternative is deployed in a 30-year period just 41 MtCO_2e would be released into the atmosphere in the Samaria II Compressors facility whereas 31 for the Cunduacan Compressors facility. However, with slight differences in the facilities under assessment, it is possible to avoid, on average, 78% of the MtCO_2e of climate pollutants with respect to deploying the OFF having 6, 10 or 15 years of OLTs. This in turn means that deploying an EGF for the case studies would avoid releasing into the atmosphere 177, 191, or 197 MtCO_2e in case of the Samaria II Compressors, whereas 134, 144 or 149 MtCO_2e in case of the Cunduacan Compressors, if an OFF with an OLT of 6, 10, or 15 years was selected instead. This number of avoided emissions is relevant due to the multiplier effect in hydrocarbon facilities, as it could happen in the Samaria-Luna PEMEX Asset where the case study is allocated at. Just in this Asset, there are 16 fields and 418 O&G-producing wells (Grupo Funcional Desarrollo Económico, 2014). Hence important GLW mitigation actions could take place in locations where is suitable to perform a change of OFFs for EGFs or complement each other prevailing the high CE criteria.

It is worth mentioning that independent of the selected flare technology, the higher the CE is, the more CO_2 emissions will be generated when flaring but also the lesser climate forcers with high GWP are released into the atmosphere. However, when the flaring is performed by OFFs the CO_2 is totally released into the atmosphere instantaneously as there are no technologies available for its capture or sequestration. In the context of GLW, whenever flaring is performed by EGFs, as a mitigation action, carbon capture, utilization, and storage (CCUS) (Agencia Internacional de Energía, 2022) technics might be implemented in the combustion chamber to manage combustion gases while taking advantage of the energy contained in such gases by Combined Heat Power (CHP) systems. Besides, further processing of flue gases exiting the EGF's combustion chamber can be achieved through the implementation of warm plasma reactors (Pacheco, Valdivia, Pacheco, & Clemente, 2020) as a novel option for diminishing the amount of CO_2 released into the atmosphere as this decarbonization capability is only available to be implemented in EGFs.

2.4.3 Health-Environment-Safety (HES) benefits

In the ongoing GLW crisis, HES concepts are tightly related to each other, and sustainability is the aim. Health-Environment-Safety-based solutions may offer affordable, sustainable benefits that can be reproduced in different locations impacting public health and social well-being (ten Brink P., 2016).

Figures 14 to **17** showed the pollutant emissions that would be released into the atmosphere in a 30-year period, considering different values of CE and operating lifetimes for both technologies. Hence, based on the findings regarding the assessed OFF and EGF, it is feasible to diminish the environmental impact on the ecosystems and the air pollution-related human diseases, morbidity, and mortality. This is by focusing on selecting high CE flaring technologies while providing the required maintenance and avoiding CE decay as directed in **Table 8**. Therefore, the better maintained and operated the flares, the higher the CE and the lesser pollutant emissions will be released. Hence, the reduction of hazardous pollutant emissions during incomplete combustion means substantial HES benefits.

HES impacts include the thermal radiation and the noise produced during the combustion reaction performed by flare technologies, more perceptible in OFFs than in EGFs (Petróleos Mexicanos, 2011) (Straitz III J. F., Burner noise and its suppression, 1991). Noise is generated simultaneously at high and low frequencies, due to distinct process parameters of the streams to be flared such as the contents of high carbon compounds and the flow stream's discharge pressure at the flare's intake. In a flaring situation. High pressures are related to high-frequency noise, whereas high carbon contents are related to low-frequency noise and are perceptible at the same time (Petróleos Mexicanos, 2011). These impacts can be better controlled or diminished in EGFs than in OFFs. Most of the time, combustion noise is a major issue, and different regulations call for flare’s acoustic noise to be less than 100 dB(A) in OFFs and 60 dB(A) in EGFs at a 30.5 m distance (Petróleos Mexicanos, 2011) (Straitz III J. F., Burner noise and its suppression, 1991).

2.5 Stage 5. Economic evaluations

For developing the economic assessment of this research work, it was required to use financial models such as the calculation of the future value (V_f) of a present value (V_p) given a discount rate (i) in a number of periods (n, quantity considered to be as a non-negative integer). The net present value (NPV) of the cash flows involved in each case study, and the benefit-cost ratio (B/C) as well **(Velayos-Morales V. , 2023)**. Those models are defined as per equations 20 to 22 **(Velayos-Morales V. , 2023)**.

$$V_f = V_p (1+i)^n \quad (20)$$

$$NPV = -I_0 + \sum_{t=1}^{n} F_t/(1+i)^t = -I_0 + (F_1/(1+i) + F_2/(1+i)^2 + \cdots + F_n/(1+i)^n) \quad (21)$$

$$B/C = NPV/I_0 \quad (22)$$

Where:
V_f = Future Value
V_p = Present Value
i = Discount rate
n = Number of periods
F_t = Cash flow at time period t
I_0 = Sum of present values of investments

NPV = Net present value
B = Benefits
C = Costs

The cash flows that are considered in this study include investments that will occur in a 30-year period due to the OFF's OLT (6, 10, and 15 years) and EGFs (25, and 30 years). A limitation of the NPV technic is that the number of periods (n) of the alternatives under assessment should be equal. Hence, when periods are not alike, the Least Common Multiple (LCM) should be used instead for performing the financial projections (Alvarado V., 2016). Convenient to stress that for numbers such as 6, 10, 15, and 30, the LCM is 30. As the LCM of numbers such as 6, 10, 15, and 25 is 150, thus the economic assessment was just focused on a 30-year period as developing it for a 150-year is impractical.

Based on the economic studies of Stone et. al (Stone, Lynch, Pandullo, Evans, & Vatavuk, 2012), the capital costs were estimated for implementing the OFF or EGF alternative in the case studies. The proposed OFF costs include a lump sum as a set of customary flare parts and components, such as flare tip, self-supported stack, pilots, flare control panel, basic instrumentation, and water seal. Under the same approach, the proposed EGF costs include the combustion chamber, pilots, set of stage valves, and arrangement of control panel and basic instrumentation.

The total investment costs (CAPEX) for the Samaria II Compressors case study respectively are 1,126,600 USD and 4,555,195 USD for the OFF and EGF, whereas for the Cunduacan Compressors case study are 958,900 USD and 3,877,133 USD correspondingly for the OFF and the EGF. Worth mentioning that these prices and all economic figures discussed herein are considered to be budgetary Class 5 cost estimations[2]. Considering the economic model developed by Stone et al (Stone, Lynch, Pandullo, Evans, & Vatavuk, 2012), **Tables 11, and 12** show an example of the CAPEX cost breakdown intended for the Samaria II Compressors facility. Similar calculations were developed for the Cunduacan Compressors facility. Hence, as a summary **Figures 18** and **19** show accordingly a graphical CAPEX breakdown for each flare and facility. To perform this economic analysis, it is assumed that the property owner already has available at no cost (for the flare upgrading project), the site preparations and the buildings where equipment and personnel will be allocated. It is also assumed that the technical crew and the auxiliary services should be the same for both flare technologies. Convenient to mention that these figures for CAPEX also become the opportunity cost for the implementation of the flare systems which are additive to the opportunity cost of recovering valuable pieces of land within the facility surrounded by different settlements.

[2] A Class 5 Cost estimation corresponds to budgetary pricing with admissible fluctuations in the range of ±40 to ±50% as per the Association for the Advancement of Cost Engineering International (AACE International).

Table 11. Example of CAPEX breakdown and factors for: Samaria II Compressors

Purchased equipment costs	**OFF Comments & factors**	**Class 5 OFF budgetary pricing**	**EGF Comments & factors**	**Class 5 EGF budgetary pricing**
Direct cost				
Flare system, equipment cost (EC)	A	447,917	A	2,546,875
Instrumentation	0.10	44,792	0.10	254,688
Sales tax	0.16	71,667	0.16	407,500
Freight	0.05	22,396	0.05	127,344
Purchased equipment cost, PEC =	**B = 0.31A**	**586,771**	**B = 0.31A**	**3,336,406**
Direct Installation costs				
Foundations and supports	0.120	70,413	0.035	116,107
Handling & erection	0.400	234,708	0.116	387,023
Electrical	0.010	5,868	0.003	9,676
Piping	0.020	11,735	0.006	19,351
Insulation	0.010	5,868	0.003	9,676
Painting	0.010	5,868	0.003	9,676
Direct Installation costs	**0.57B**	**334,459**	**0.165B**	**551,508**
Site preparation & building costs				
Site preparation	SP	0	SP	0
buildings	Bldg.	0	Bldg.	0
Total direct costs, DC =	**1.57B + SP + Bldg.**	**921,230**	**1.165B + SP + Bldg.**	**3,887,914**
Indirect cost (installation), IC				
Engineering	0.10	58,677.08	0.050	166,820
Construction and field expenses	0.10	58,677.08	0.050	166,820
Contractor fees	0.10	58,677.08	0.050	166,820
Start-up	0.01	5,867.71	0.010	33,364
Performance test	0.01	5,867.71	0.010	33,364
Contingencies	0.03	17,603.13	0.030	100,092
Total indirect costs, IC	**0.35B**	**205,369.79**	**0.2B**	**667,281**
Total investment cost, TIC = DC + IC =	**1.92B+SP+Bldg.**	**1,126,600.00**	**1.3653B+SP+Bldg.**	**4,555,195**

Source: Own work

Table 12. Example of expenditures breakdown for Samaria II Compressors

Total investment costs (Million USD)		
Parameter	**OFF**	**EGF**
Initial capital cost	0.587	3.336
Commissioning/Decommissioning (year 0)	0.540	1.219
Σ =	**1.127**	**4.555**

Source: Own work

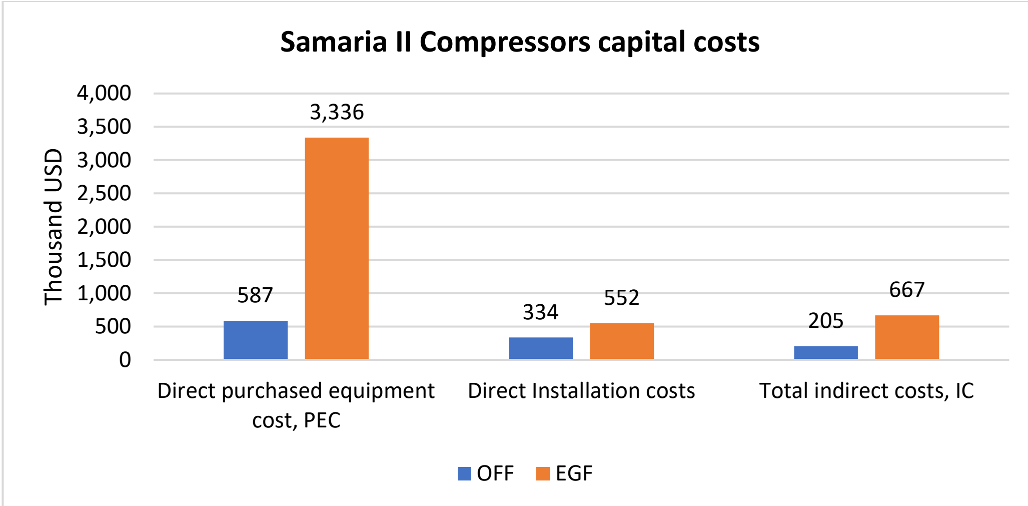

Fig. 18. Samaria II Compressors OFF and EGF CAPEX
Source: Own work

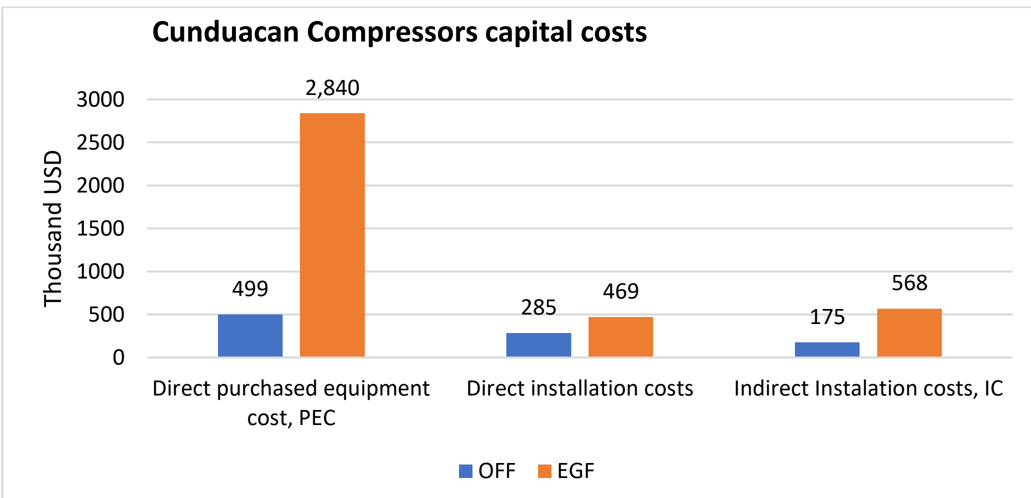

Fig. 19. Cunduacan Compressors OFF and EGF CAPEX
Source: Own work

Based on the same economic models used so far, in regard to the operating and maintenance cost estimations for the technologies under assessment, **Tables 13, and 14** show an example of the OPEX breakdown developed for the Samaria II Compressors case study. Similar estimations were carried out for the Cunduacan Compressors case study.

Table 13. Considerations for the OPEX breakdown

Parameter	Unit	Value
Interest/discount rate		10.00%
Operator Labor rate:	USD per hour	29.63
Maintenance labor rate:	USD per hour	25.12
Estimated equipment operating lifetime (OLT):	year	OFF: 6, 10, 15; EGF: 30
Expected Number of Operator Labor Hours Annually:	hours/year	630
Expected Number of Maintenance Labor Hours per Shift:	hours/shift	0.5
Total annual hours:	hours/year	100

Source: Own work

Table 14. Example of Operating and Maintenance (OPEX) cost breakdown for Samaria II Compressors

Estimated annual O&M costs (USD) & factors for OFF & EGF flare systems					
Cost item	**Factor**	**OLT: 6 years, OFF**	**OLT: 10 years, OFF**	**OLT: 15 years, OFF**	**OLT: 30 years, EGF[2/]**
Direct annual costs, DC	**Comment**				
Operating labor					
Operator	630 man-hours/year	$18,667	$18,667	$18,667	$18,667
Supervisor	15% of operator	$2,800	$2,800	$2,800	$2,800
Operating materials					
Maintenance					
Labor	1/2 hours per 8-hour shift	$0	$79	$157	$157
Materials	100% of maintenance labor	$0	$79	$157	$157
Utilities					
Electricity	(consumption rate) x (hours/year) x (unit cost)	0	0	0	0
Purge gas	(consumption rate) x (hours/year) x (unit cost)	$33	$33	$33	$33
Pilot gas	(consumption rate) x (hours/year) x (unit cost)	$16	$16	$16	$16
Auxiliary fuel	(consumption rate) x (hours/year) x (unit cost)	0	0	0	0
Steam	(consumption rate) x (hours/year) x (unit cost)	0	0	0	0
	Direct annual cost, **DC:**	$21,517	$21,674	$21,831	$21,831
Indirect annual costs, IC					
Overhead	60% of total labor and materials cost	$12,880	$12,974	$13,069	$13,069
Administrative Charges	2% of capital investment	$22,532	$22,532	$22,532	$22,776
Property tax	1% of capital investment	$11,266	$11,266	$11,266	$11,388
Insurance	1% of capital investment	$11,266	$11,266	$11,266	$11,388
Capital recovery[1/]	0.2296 (OLT 6), 0.1627 (OLT 10), 0.1315 (OLT 15), 0.1061 (OLT 30) of capital investment	$258,676	$183,349	$148,118	$241,606
	Indirect annual cost, **IC**:	$316,620	$241,387	$206,251	$300,226
Total annual cost, DC + IC	**Sum of direct and indirect annual costs:**	**$338,136**	**$263,061**	**$228,081**	**$322,057**

1/ Capital recovery factor varies upon interest rate (i) and number or periods (n). [i × (1 + i)n] / [(1 + i)n - 1]. For this assessment i = 10%, n = OLT
2/ Escalation factor used when applicable due to the technology due to area reductions and emission reductions

Source: Own work

Figures 20 and **21** show for the case studies the calculated annual operation and maintenance (O&M) costs to be used as reference data in the economic calculations for assessing the performance of the two flares. for OLT scenarios of 6, 10, or 15 years in the case of OFFs, and 30 years in the case of EGFs.

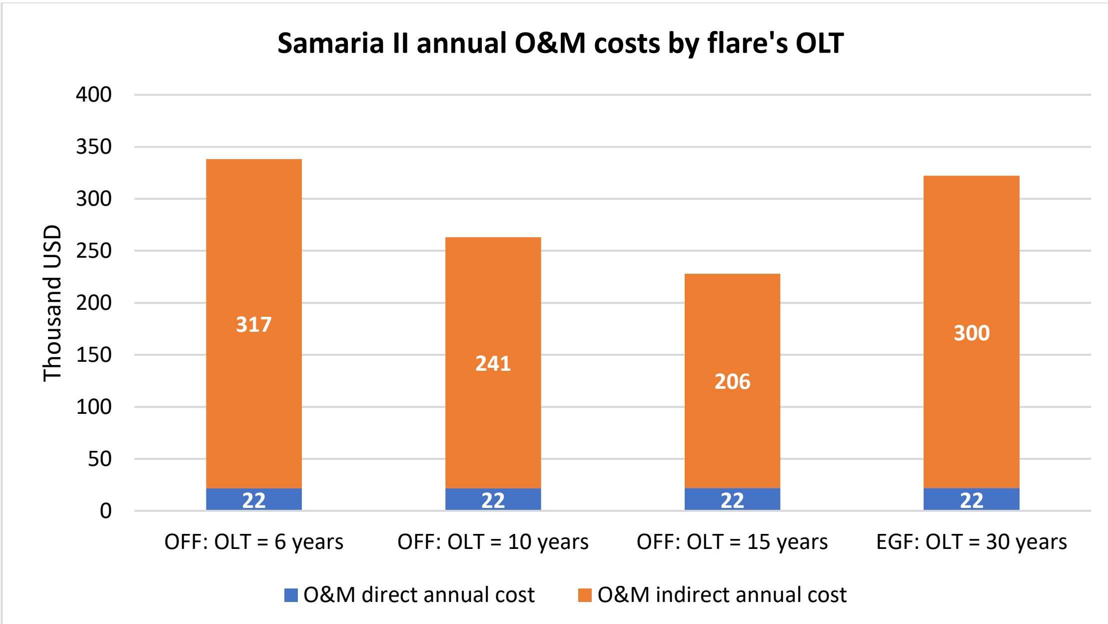

Fig. 20. Samaria II Compressors OFF's and EGF's direct and indirect annual O&M costs
Source: Own work

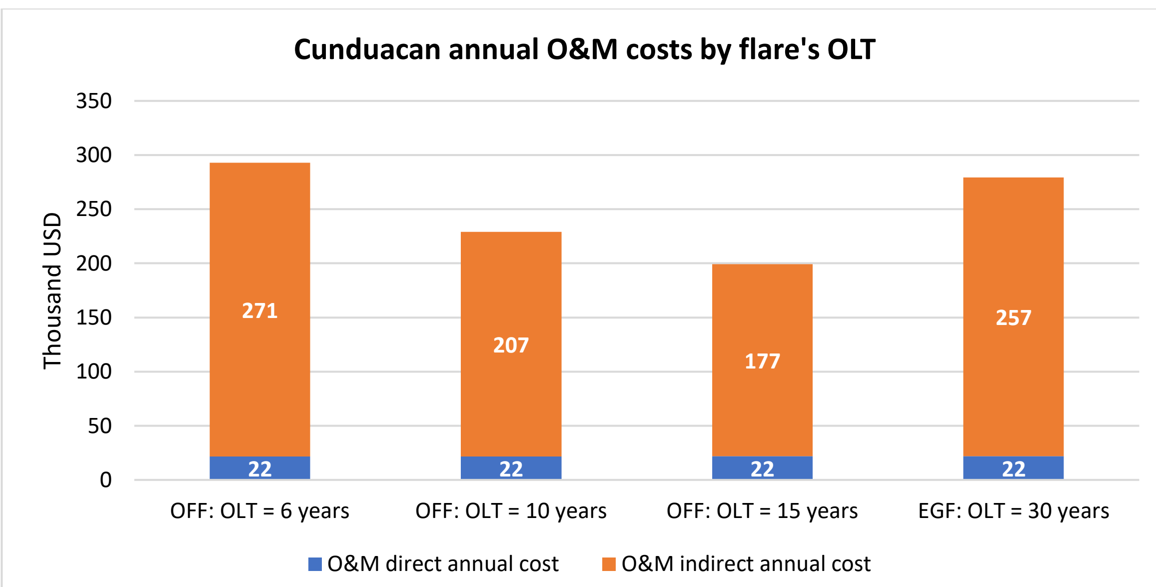

Fig. 21. Cunduacan Compressors OFF's and EGF's direct and indirect annual O&M costs
Source: Own work

The economic assessment performed in this section required the development of different financial runs for each flare technology considering the CAPEX, OPEX, and OLT for each case study. **Table 15** shows as an example, the financial run for the Samaria II Compressors facility considering an OFF's OLT of 10 years. Worth mentioning that similar runs were developed for all OLTs in both case studies.

Table 15. Example of financial run breakdown for Samaria II Compressors

OFF & EGF financial run (Million USD) for OFF: OLT = 6 years in a 30-year period

Year	Concept	OFF[1/]	EGF[2/]
0	Investment & annual expenses at year 0	1.465	4.877
1	Annual expenses at year 1	0.372	0.354
2	Annual expenses at year 2	0.409	0.390
3	Annual expenses at year 3	0.450	0.429
4	Annual expenses at year 4	0.495	0.472
5	Annual expenses at year 5	0.545	0.519
6	Investment & annual expenses at year 6	2.595	0.571
7	Annual expenses at year 7	0.659	0.628
8	Annual expenses at year 8	0.725	0.690
9	Annual expenses at year 9	0.797	0.759
10	Annual expenses at year 10	0.877	0.835
11	Annual expenses at year 11	0.965	0.919
12	Investment & annual expenses at year 12	4.597	1.011
13	Annual expenses at year 13	1.167	1.112
14	Annual expenses at year 14	1.284	1.223
15	Annual expenses at year 15	1.412	1.345
16	Annual expenses at year 16	1.554	1.480
17	Annual expenses at year 17	1.709	1.628
18	Investment & annual expenses at year 18	8.144	1.791
19	Annual expenses at year 19	2.068	1.970
20	Annual expenses at year 20	2.275	2.167
21	Annual expenses at year 21	2.502	2.383
22	Annual expenses at year 22	2.753	2.622
23	Annual expenses at year 23	3.028	2.884
24	Investment & annual expenses at year 24	14.427	3.172
25	Annual expenses at year 25	3.664	3.489
26	Annual expenses at year 26	4.030	3.838
27	Annual expenses at year 27	4.433	4.222
28	Annual expenses at year 28	4.876	4.644
29	Annual expenses at year 29	5.364	5.109
30	Annual expenses & decommissioning at end of year 30	15.320	5.620
	Amount expended in the 30-year period:	95.0	63.2
	Net Present Value (NPV):	**19.64**	**16.21**
	Benefit-Cost Ratio (NPV/Io):	**3.49**	**3.32**
	NPV_{EGF}/NPV_{OFF}:		***0.8253***

1/ OFF's OLT = 6 years

2/ EGF's OLT = 30 years

Source: Own work

As can be noted in **Table 15**, for the 30-year time frame of the analysis regarding the Samaria II Compressors facility, considering an OFF's OLT to be 6 years, the total OFF's expenditures sum 95 million USD (MUSD), whereas the total EGF expenditures sum 63.2 (MUSD). The discount rate (i) employed for this assessment was 10%. As a result of this assessment, by using **Equations 20, 21**, and **22**, the net present value (NPV) and the benefit-cost (B/C) ratio were calculated as financial indicators for both flares. The OFF's NPV is found to be 19.64 MUSD with a B/C of 3.49, while the EGF's NPV is 16.21 MUSD and its B/C is 3.32. As NPV> 0 and (B/C)>1, both investment scenarios are acceptable from the economic engineering standpoint (Alvarado V., 2016) (Centro de Estudios para la Preparación y Evaluación Socioeonómica de Proyectos (CEPEP) de la Secretaría de Hacienda y Crédito Publico (SHCP), 2017) (Nacional Financiera (NAFINSA), Banca de Desarrollo, 2004). Similar calculations were performed for the Cunduacan Compressors facility, thus **Figures 22** and **23** illustrate the results obtained for each facility. As can be noted, in the long term for both cases the O&M represents the bulk part of the expenditure although the initial investment is a small part of the total disbursement. Although the NPV is an inverse function of the discount rate, the larger the NPV is, the larger the cost of opportunity is as well (Centro de Estudios para la Preparación y Evaluación Socioeonómica de Proyectos (CEPEP) de la Secretaría de Hacienda y Crédito Publico (SHCP), 2017) and a project's financial risk is proportional to NPV (Ludeña, 2021). By using the same financial models, from the NPV perspective, the results shown in **Figures 22,** and **23** mean that investing in both technologies is feasible with a reasonably similar financial risk.

It can be said that investing in OFF technology could be acceptable in the long term as per the B/C criteria, whenever the combustion efficiency and performance are ensured to be above 99% all over the OFFs' OLT. However, if high CE cannot be achieved or ensured, then OFFs should be frequently replaced making them a not sustainable investment and the price that will be paid is generating a large amount of pollutant emissions, as discussed in Sections 3.3 and 3.4. Hence, deploying EGFs has a lower environmental risk and means investing in cleaner technologies that make both economic and environmental sense.

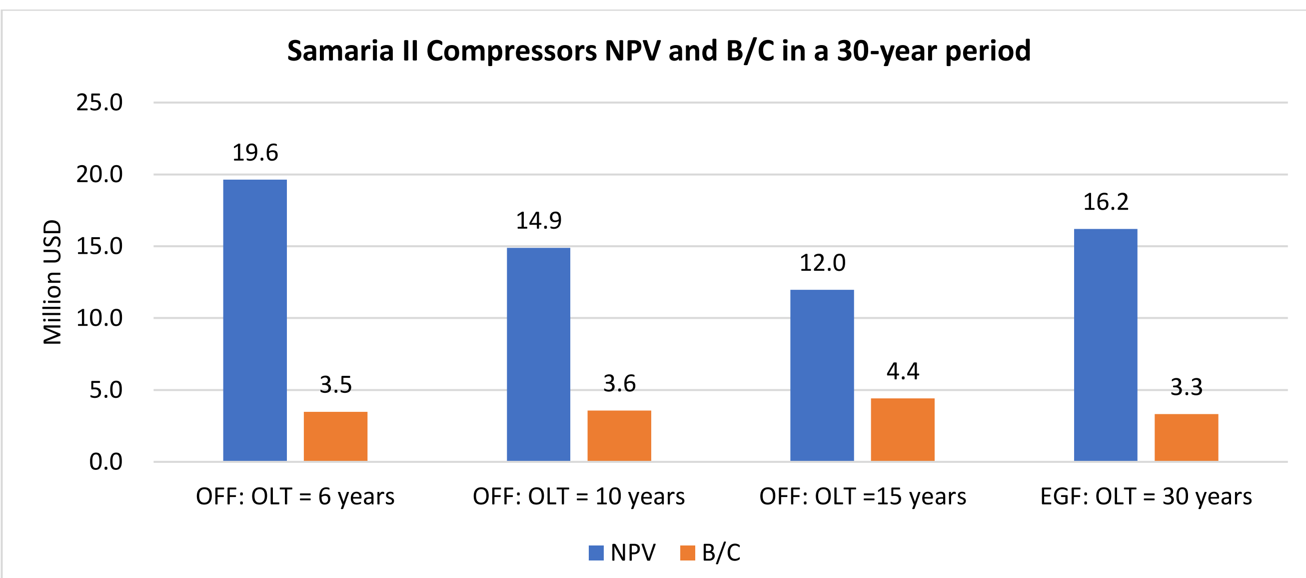

Fig. 22. Samaria II Compressors economic indicators by flare's operating lifetime
Source: Own work

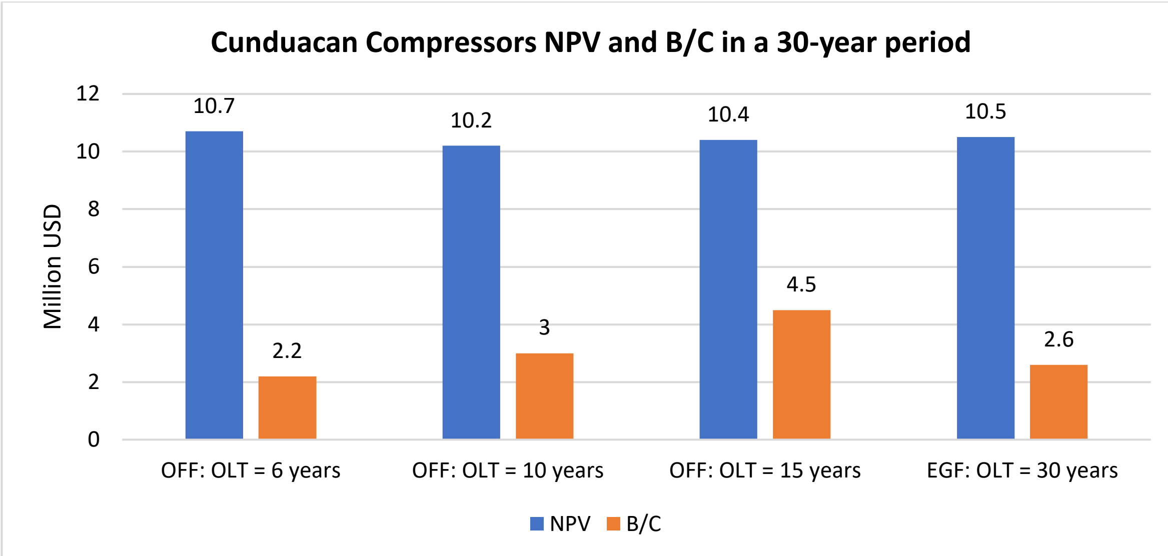

Fig. 23. Cunduacan Compressors economic indicators by flare's operating lifetimes
Source: Own work

Deployment of EGFs is happening more often than in the past due to aesthetic reasons but more importantly for their better destruction efficiencies even with the higher CAPEX (Coalbed Methane Outreach Program, US EPA, 2014) and lesser B/C financial indicator. Investing in OFFs and EGFs is feasible from a financial standpoint, but in the long term, as per B/C criteria, EGFs mean less financial risk than OFFs. However, in today's world, financial aspects should be considered, as other aspects such as environmental remediation costs, GLW resiliency costs, carbon taxation, carbon credits, and Environment-Society-Governance (ESG) financial cost among others. Hence, reducing pollutant emissions by selecting the right flare technology means implementing cleaner engineered solutions that in the long term (30-year period in our case) represent substantial economic benefits for whole the stakeholders.

2.6. Stage 6. OFF and EGF key findings

The methodology proposed in this document provides a useful way to compare the OFF technologies commonly used in the Mexican O&G industry, in regard to a modern but mature alternative that provides larger environmental benefits such as the EGF technologies.

Some of the environmental key findings can be noted in **Figures 14 to 17,** due to their CE, EGFs perform better than OFFs from the pollutant emissions standpoint. EGFs avoid releasing into the atmosphere large amounts of climate forcers in a 30-year period, considering the OLT scenarios for OFFs and EGFs. **Table 16** summarizes the key findings of this research work regarding OFFs and EGFs assessed through the case studies. Based on **Table 3,** it was determined that in a 30-year period the mass flows sent to the flares are 521.4 and 340.4 MtCO_2e correspondingly for Samaria II and Cunduacan case studies.

Table 16. OFF vs EGF key findings

Context	Area of Evaluation	Key finding
Technology	Flare physical dimensioning	OFFs and EGFs may carry out the combustion under similar flaring conditions
		EGF needed 1.3% and 1.4% of flaring area for Samaria II and Cunduacan, respectively.
	Technical compatibility	EGFs are compatible and may support CHP, CCUS, and plasma reactor technologies for emission reductions whereas OFFs are not.
Safety	Consequence analysis	EGFs' heat release distances are less than OFFs due to the capabilities of the combustion chamber
Environment	Hydrocarbon released emissions	Due to combustion inefficiency (1-CE), OFFs releases of unburned hydrocarbon are on average 24% of the total flow stream directed to the flare in a 30-year period, whereas only 5% for EGFs
	Hydrocarbon avoided emissions	Due to combustion efficiency (CE), OFFs may avoid 76% of the hydrocarbon emissions in a 30-year period, whereas EGFs avoid 95% of such emissions
	CO_2e released emissions @ high combustion efficiency	If flare technologies are properly operated and CE maintained in numbers in excess of 0.99, the released CO_2e emissions should be below 3% avoiding 97% of the pollutant emissions
	CO_2e released emissions when CE decays	Due to combustion inefficiency (1-CE), OFFs releases of CO_2e are an average of 23.2% of the total flow stream directed to the flare in a 30-year period, whereas only 5% for EGFs
	CO_2e avoided emissions when CE decays	Due to combustion efficiency (CE), OFFs may avoid 76.8% of the hydrocarbon emissions in a 30-year period, whereas EGFs avoid 95% of such emissions
	Criteria pollutants avoided emissions	On average EGS release 70% less emissions of CO, NO, and NO_2 than OFFs
Finance	Initial investment	The initial investment for EGFs is more expensive than for OFFs. For the case studies: 5.7 times the capital cost and 2.3 times the commissioning expenses.
	Levelized expenses in a 30-yer period	Given the operating lifetime (6, 10, or 15 years) for OFFs to cover a 30-year period, for the Samaria II case study the levelized cost of avoided pollutant emission is 0.131 USD/tCO_2e. Whereas for the Cunduacan case study the levelized cost of avoided pollutant emission is 0.177 USD/tCO_2e.
	Accumulated investment and expenses in a 30-year period	For a 30-year period, the cash flow required in Samaria II for OFFs will range from 95 to 58 MUSD upon the life expectancy, whereas for EGFs the required cash flow is 59 MUSD. In Cunduacan the cash flow for OFFs will range from 82 to 50 MUSD upon the life expectancy, whereas for EGFs the cash flow require 55 MUSD. In both cases for a 30-year period, O&M roughly represent 93% of the total expenses.
	NPV and B/C criteria	In the long term, EGFs represent similar financial risk to OFFs.

Source: Own work

Based on the information displayed in **Table 16**, **Figures 16** and **17, Table 17** shows the costs per avoided pollutant emissions (USD/tCO_2e), corresponding to EGF technologies the lowest values being 0.13 and 0.18 USD/tCO_2e respectively for the Samaria II and Cunduacan Compressors facilities

Table 17. OFF vs EGF costs associated per avoided emissions in a 30-year period

		Samaria II Compressors				Cunduacan Compressors			
Flare technology	**OLT**	**Total Expenditures**	**Released emissions**	**Avoided emissions**	**Cost per avoided hydrocarbon emissions**	**Total expenditures**	**Released emissions**	**Avoided emissions**	**Cost per avoided hydrocarbon emissions**
(Set)	**(Year)**	**(MUSD)**	**($MtCO_2e$)**	**($MtCO_2e$)**	**(USD/tCO_2e)**	**(MUSD)**	**($MtCO_2e$)**	**($MtCO_2e$)**	(USD/tCO_2e)
OFF	**6**	95.0	177	344	**0.28**	81.8	134	206	**0.40**
OFF	**10**	71.6	191	330	**0.22**	61.9	144	196	**0.32**
OFF	**15**	57.9	197	324	**0.18**	50.3	149	191	**0.26**
EGF	**30**	63.2	41	480	**0.13**	54.7	31	309	**0.18**

Source: Own work

2.7 Comparative cost assessment between OFF and EGF

Stage 7 of our Methodology calls for a comparative cost assessment which is presented in **Table 18** considering the cost calculations developed in this work for the case studies' OFFs and EGFs in a 30-year period by the operating lifetime for each technology.

Table 18. OFF vs EGF comparative assessment of costs as a function of the OLT in a 30-year period

		Samaria II Compressors		Cunduacan Compressors	
Evaluation item	**OLT (years)**	**OFF[2/]**	**EGF[2/]**	**OFF[2/]**	**EGF[2/]**
Capital cost		0.587	3.336	0.499	2.840
Commissioning/Decommissioning		0.540	1.219	0.459	1.037
Annual O&M expenses[1/]	6	0.338		0.293	
	10	0.263		0.229	
	15	0.228		0.199	
	30		0.322		0.279
Accumulated O&M expenses on a 30-year period[1/]	6	61.5		53.3	
	10	47.9		41.7	
	15	41.5		36.3	
	30		58.6		50.8
Accumulated investment and O&M expenses on a 30-year period[1/]	6	95.0		81.8	
	10	71.6		61.9	
	15	57.9		50.3	
	30		63.2		54.7
Net Present Value (NPV) on a 30-year period[1/]	6	19.6		16.9	
	10	14.9		12.9	
	15	12.0		10.4	
	30		16.2		14.0
Benefit-Cost ratio (B/C) on a 30-year period[1/]	6	3.5		3.5	
	10	3.6		3.6	
	15	4.4		4.5	
	30		3.3		3.4

1/ Values calculated considering i = 10%, n = OLT. The 30-year estimations considered a cyclic updated reposition of goods and services at the end of each OLT

2/ Values in Million USD (MUSD)

Source: Own work

3. Visualizations of relevant results

Figures 24, **25**, and **26** are self-explanatory and show a graphic representation of **Table 17** as a summary of the relevant results of this research work.

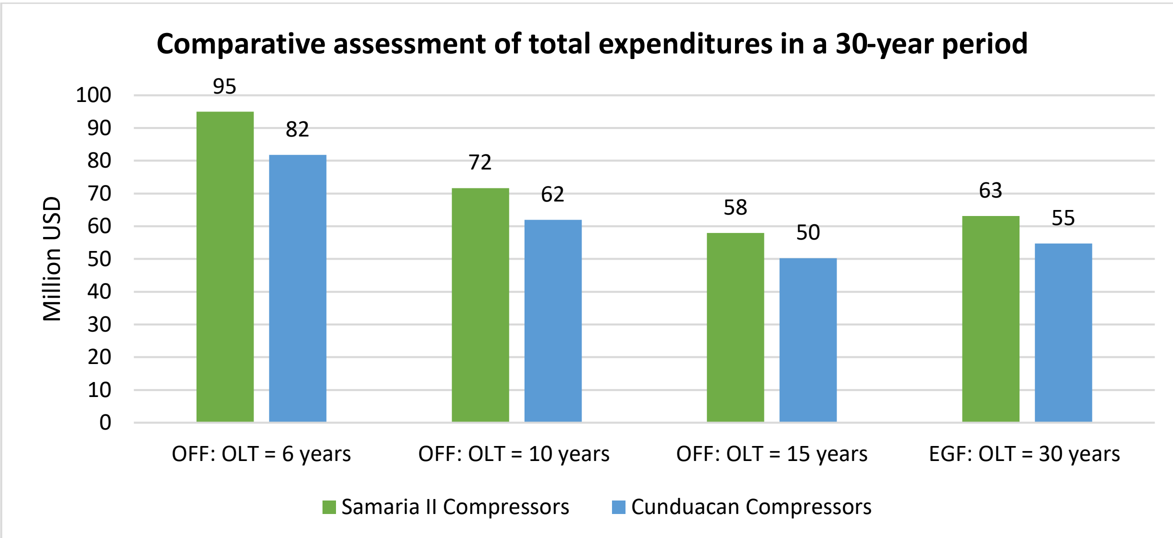

Fig. 24. Total expenditures including equipment investment and O&M by OLT
Source: Own work

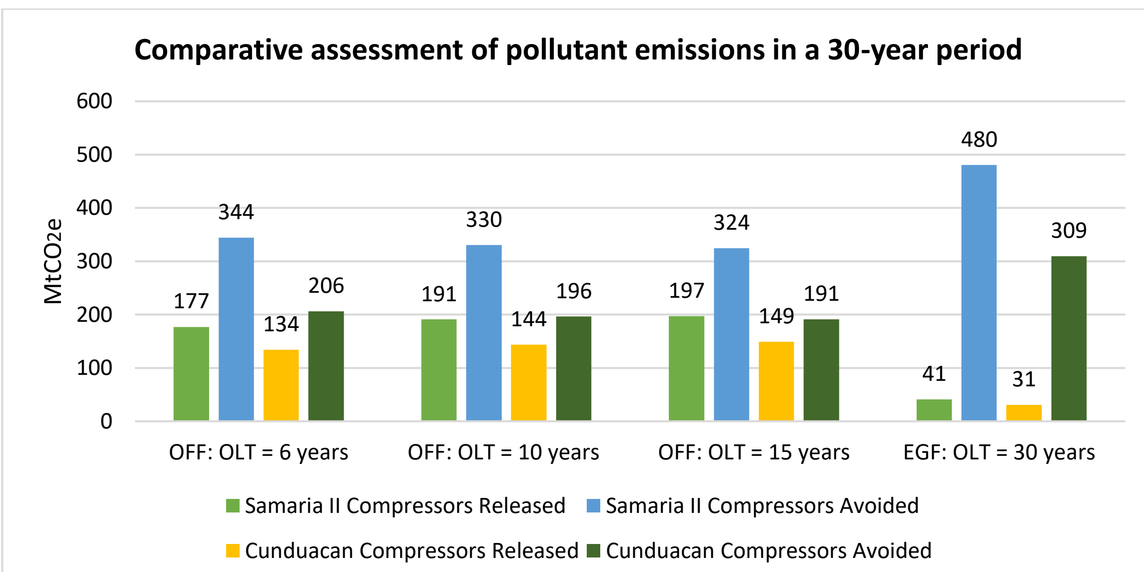

Fig. 25. Balance of released vs. avoided pollutant emissions by flare's operating lifetime
Source: Own work

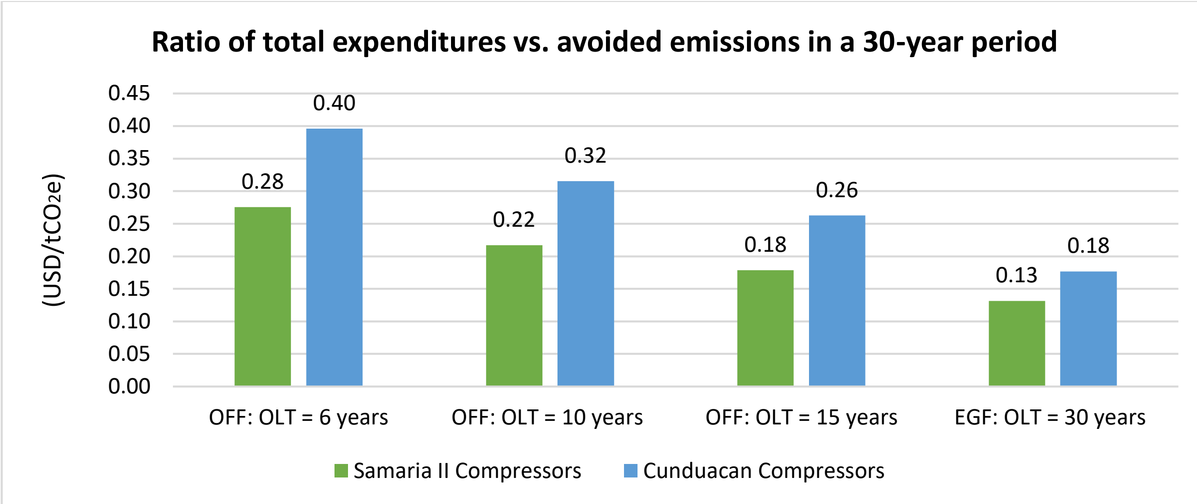

Fig. 26. Cost of avoided pollutant emissions in a 30-year period

Source: Own work

4. Conclusions

The hydrocarbon sector must become more environmentally sustainable by using mature but cleaner gas-flaring technology such as EGFs. The proposed methodology is used to assess the technical benefits and costs of the very often used OFFs versus the modern but mature EGFs technologies.

Implementing an EGF could allow recovery and use the thermal energy released during gas flaring in hydrocarbon facilities, a situation that is not possible with OFFs. Deploying EGF technologies also eliminates acoustic and luminous radiation that OFF technologies cannot avoid, providing additional HES benefits.

OFFs are more sensitive to a lack of maintenance and crosswind loads, causing faster combustion efficiency decay, whereas EGFs are more resilient to those situations. Considering an ideal case, in which both technologies perform combustion with high efficiency, CO_2 emissions would be reduced by 97% when flares operate at 99.9% of CE. However, only 74.5% of CO_2e emissions could be avoided when CE is 50% and this happens very frequently in OFFs without maintenance or poor maintenance. Such low values of CE along with insufficient maintenance also increase the risks that the facilities will be exposed to as noted in the simplified HAZOP analysis included in this research work.

Based on the consequence analysis performed by using the PHAST tool, the simulated failures potentially occurring in the EGF would be contained within their combustion chamber. Whereas the affected area due to a failure in the OFF is in an open area surrounding the flare structure, where personnel, equipment, and ecosystems would be exposed to danger.

The initial capital cost for EGFs is several times the OFF’s initial cost, however, in a 30-year period, the NPV and B/C criteria show that investing in the EGF reduces the long-term expenses and increases benefits, even more when considering carbon credits or carbon taxation mitigation. Just one EGF with a 30-year operating lifetime could replace up to five 5 OFFs when their operating lifetimes are reduced to 6 years, because of the drastic decreasing efficiency commonly occurring in OFF-type gas flares.

EGF technology tends to avoid unburned hydrocarbon emissions which means aiding the decarbonization strategies of the sector. Deploying EGF technologies provides the lowest levelized cost of avoided emissions per tCO_2e while lessening the carbon-tax exposure of hydrocarbon facility owners and increasing the carbon-credit market.

As discussed in this thesis, when flaring cannot be avoided in the O&G industry, the results obtained through an integrated assessment in our proposed methodology show that the adoption of EGF technologies is an immediate and sustainable global warming mitigation action that reduces emissions, which in turn will bring operational, environmental, social, economic, and risk-reduction benefits. This benefits the industry, community, and environment and not only the owner/operator of the hydrocarbon facilities.

The results of this study accomplish the proposed objectives and prove as truth the hypothesis which this research work was based on. Justifying our study while reaching the proposed scope to determine the minimum amount of CO_2 and pollutant emissions that would no longer be sent into the atmosphere in hydrocarbon facilities when replacing OFFs by EGFs.

5. Recommendations

Based on the it is recommended that the stakeholders involved in the design, operation and maintenance of hydrocarbon facilities with flares devote stronger efforts for ensuring the high CE of their flares and reducing air pollutant emissions. It is also recommended, that prior to select a flare technology for a hydrocarbon facility, to apply the methodology developed in this study for assessing the flare to be selected that could be more suitable, while analyzing what advantages could be achieved in their facilities, i.e., technical, environmental, economic and safety benefits when deciding on one flare technology over the other.

Additionally, it is recommended that future work related to this assessment include assessing the capture of CO_2 produced during gas flaring for enhanced oil recovery (EOR) and CHP electrical power generation systems along with plasma reactor systems and CCUS strategies.

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7. Glossary of key concepts

Concept	Abbreviation	Definition	Web site link
Alkane hydrocarbons	C_xH_y	Alkanes are compounds that consist entirely of atoms of carbon and hydrogen bonded to one another by carbon-carbon and carbon-hydrogen single bonds.	https://www.sciencedirect.com/topics/earth-and-planetary-sciences/alkane
Benefit/Cost ratio	B/C	The benefit-cost ratio (BCR) is a ratio used in a cost-benefit analysis to summarize the overall relationship between the relative costs and benefits of a proposed project.	https://www.investopedia.com/terms/b/bcr.asp
Burner		Device that is a component of a flare system where the combustion is physically occurring	
Capital Cost	CAPEX	Essentially, capital costs are one-time expenses paid for things used in the production of goods or service. A good example of capital costs is the purchase of fixed assets, like new buildings or business tools. It could also include the costs of intangible assets, like patents and other forms of technology.	https://quickbooks.intuit.com/global/glossary/capital-cost/
Combustion efficiency	CE or η	Combustion efficiency is a measurement of how well the fuel being burned is being utilized in the combustion process.	https://trutechtools.com/Understanding-Combustion-Efficiency_c_261.html
Enclosed ground flare	EGF	EGFs conceal the flames from a direct view within a combustion chamber at ground level	https://doi.org/10.1016/j.clet.2023.100671
Flame length	L_f	Length of the flame produced during the combustion process in a flare system	https://doi.org/10.1016/j.clet.2023.100672
Hydrocarbon combustion		Hydrocarbon combustion refers to the chemical reaction where a hydrocarbon reacts with oxygen to create carbon dioxide, water, and heat.	https://energyeducation.ca/encyclopedia/Hydrocarbon_combustion
Net Heating Value	NHV	Net Heating Value or its abbreviation "NHV" means the quantity of heat, expressed in Btu or Kcal, produced by the complete combustion at constant pressure of one (1) Standard Cubic Meter of Gas, with the air at the same temperature and pressure as the Gas and all the water formed by combustion reaction remaining in the vapor state.	https://www.lawinsider.com/dictionary/net-heating-value
Net Present Value	NPV	Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.	https://www.investopedia.com/terms/n/npv.asp
Open Flame Flare	OFF	A flare system generally consists of an elevated stack, means to maintain burning conditions at the top of stack, and means to prevent flashback within the system.	https://www.sciencedirect.com/topics/engineering/flare-system
Operating Lifetime	OLT	Period of time in which the flare system is operating after start-up and commissioning, before is replaced for a new one.	https://doi.org/10.1016/j.clet.2023.100671
Operational and maintenance expenditures	OPEX	An operating expense is an expense that a business incurs through its normal business operations. Often abbreviated as OPEX, operating expenses include rent, equipment, inventory costs, marketing, payroll, insurance, step costs, and funds allocated for research and development.	https://www.investopedia.com/terms/o/operating_expense.asp

Self elaboration

8. References

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