Life cycle GHG emissions analysis of the LNG export project, Saguaro Energía.

INICIATIVA CLIMÁTICA DE MÉXICO

Index

Abbreviations and acronyms

ACV	life cycle analysis
CC	combined cycle
CH_4	methane
CO_2	carbon dioxide
COP	Conference of the Parties
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EUR	estimated ultimate recovery
FE	emission factor
GEI	greenhouse gases
GHGRP	Greenhouse Gas Reporting Program
LNG	liquefied natural gas
ICCT	International Council on Clean Transportation
BWI	Mexico Climate Initiative
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LHV	low heating value
MIA	Environmental Impact Statement
NDC	Nationally Determined Contributions
NETL	National Energy Technology Laboratory
NGSI	Natural Gas Sustainability Initiative
NZE	Net-Zero Emissions Scenario
PCG	global warming potential
PEMEX	Petróleos Mexicanos
TG	open cycle with gas turbine
U.S. DOT	U.S. Department of Transportation

Units

Btu	british thermal unit
MMBtu	million Btu
g	gram
kg	kilogram
Mg	megagram
Gg	gigagram
gal	gallon
GW	gigawatt
hp	horsepower
hp-h	horsepower-hour
kJ	kilo joule
MJ	mega joule
km	kilometer
kWh	kilowatt-hours
MWh	megawatt-hours
m^3	cubic meter
t	ton
Mt	million tons
tCO_2e	ton of carbon dioxide equivalent
$MtCO_2e$	million tons of carbon dioxide equivalent
Mtpa	million tons per year
MW	megawatt
scf	standard cubic foot
MMscf	million standard cubic feet

Executive summary

The production surplus and low natural gas prices [1] in North America have changed the international energy landscape in recent years, and the United States has become a net exporter of this fuel. Although the main market for this natural gas has been Europe, markets in Asia have shown interest in increasing their imports due to the low price of natural gas produced in the United States and the convenience of exporting it from the Pacific without crossing Panama Canal. For this reason, the expansion of natural gas liquefaction infrastructure for export from intermediary countries such as Canada or Mexico has been promoted. Among the natural gas export projects proposed for Mexico is the Saguaro Energía project, planned for Puerto Libertad (state of Sonora), which is analyzed in this paper. The project seeks to liquefy in Mexico the natural gas coming from the Permian Basin in the United States for its subsequent maritime transportation and use in Asia. It should be noted that this is not the only project under development and that there are currently other projects in Baja California (Energía Costa Azul), Sinaloa (Vista Pacífico LNG) and Sonora (Epcilon LNG, AMIGO Terminal) (U.S. DOE, Office of Fossil Energy and Carbon Management, 2024).

However, this could prevent exporting countries from meeting their greenhouse gas (GHG) emissions mitigation goals, since this type of project not only encourages the burning of this fuel but also the generation of methane emissions, a greenhouse gas with a global warming potential several times greater than that of CO_2, which is emitted into the atmosphere during the entire life cycle of natural gas. In this work, a life cycle analysis (LCA) was performed with respect to the GHG emissions of the Saguaro Energía project and the entire natural gas supply chain, from its production to its use in Asia. For this purpose, the methodology used was based ISO 14044:2006 for the development of LCAs.

The results obtained from the LCA show that the use of natural gas accounts for most of the GHG emissions. Therefore, the functional unit[2] was defined as one ton of natural gas to be used for electricity generation. If maritime transportation with steam-powered ships (from the combustion of natural gas and fuel oil) is considered, the carbon footprint corresponds to 1,761 tons of CO_2e (tCO_2e) per ton of natural gas. Considering maritime transportation through ships with 4-stroke and 2-stroke engines (operating only with natural gas), the carbon footprint is 1,399 tCO_2e per ton of natural gas and 1,347 tCO_2e per ton of natural gas.

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[1] We use the term "natural gas" throughout this report because it the term commonly used internationally to refer to the material at hand: a gaseous fossil fuel, composed mostly of methane. This material is also often referred to as "fossil gas" or "methane gas," although it usually contains some components other than methane, such as other hydrocarbons, hydrogen sulfide, mercury, carbon , and water vapor.

[2] In life cycle analysis (LCA), it refers to the amount of product, in this case natural gas to be used in electricity generation, which is used to compare different alternatives that can generate this natural gas. Its selection is based on typical measurement units for this product.

natural gas, respectively. The natural gas use, production and processing stages of natural gas in the United States account for more than half of the total carbon footprint estimated in this study[3]. The carbon footprint for maritime transport is higher in the case of steam-powered ships compared to liquefaction, while the opposite is true for the other two cases. This is due to the impact of the use of fuel oil for maritime transport in steam-powered ships.

The project analyzed in this paper could represent a barrier to climate efforts, potentially delaying the implementation of wind or solar projects. If this gas were to reach the market, it could displace the potential installation of up to 37.7 GW of installed wind capacity or 54.4 GW of installed solar PV capacity. This 11% and 7% of the capacity required, respectively, to achieve the International Energy Agency's (IEA) net-zero emissions scenario.

Total annual emissions from the project would be approximately 73 $MtCO_2e$, or the equivalent of 17.34 million light-duty vehicles driven during one year (U.S. EPA, 2024). For emissions generated within Mexican territory, the project would increase CO_2e emissions from the oil and gas sector, and thus national emissions by 5.4 $MtCO_2e$ per year, which is equivalent to almost 8% of the direct emissions of Petróleos Mexicanos (PEMEX) in 2022 (PEMEX, 2024), or the emissions from more than 1.28 million light vehicles driven during one year (U.S. EPA, 2024) see Figure). It is important to note that this natural gas will be used in Asia, and Mexico will only serve as a means of transportation and therefore, the economic contribution to the country is marginal.

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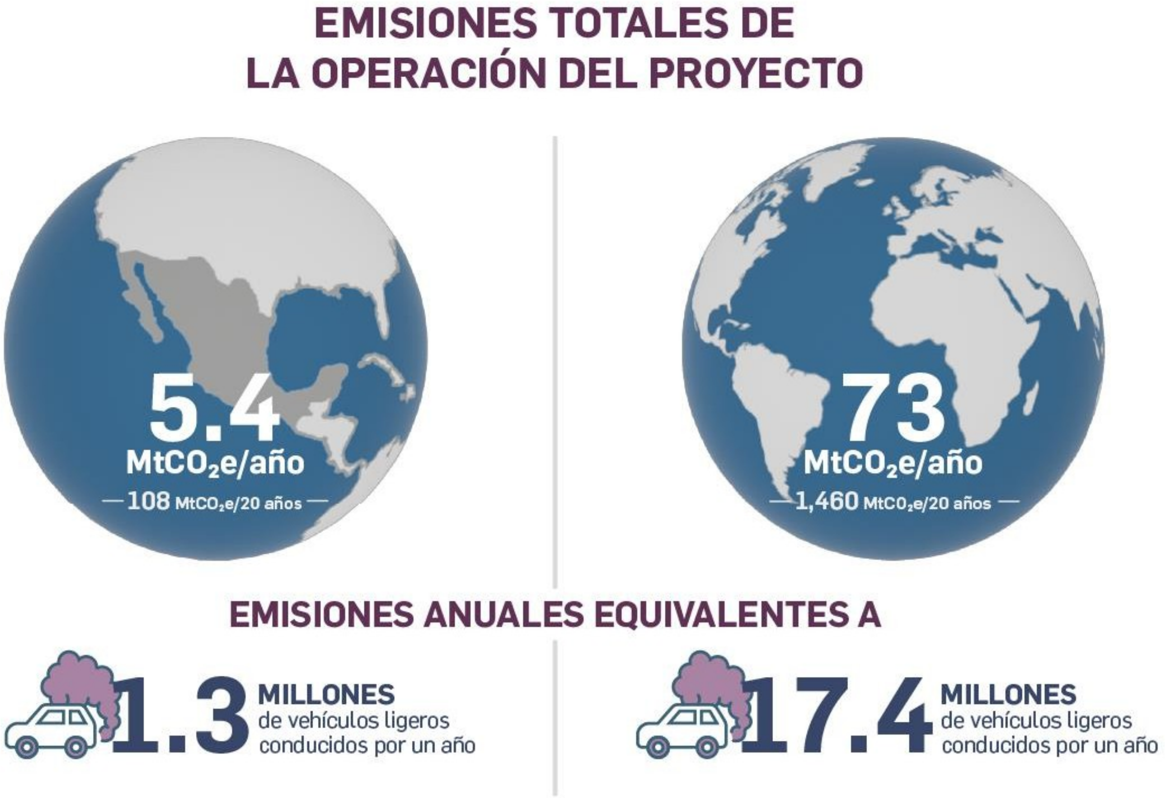
[3] Natural gas extraction and production, transportation in the United States and Mexico, liquefaction in Mexico, transportation to Asia and regasification.

Total emissions from the operation of the project during one year and accumulated in 20 years, liquefaction capacity of 15 Mtpa.



Given the magnitude of the project and the actions required to achieve net zero emissions, the project is relevant and it will be necessary to find alternatives to stop the expansion of the use of fossil fuels or to promote the accelerated development of carbon-free sources. It is also necessary to quantify in greater detail the environmental impact of the project, as well as the impact of the expansion of the company's planned future operations in the region.

1. Introduction

1.1. Global natural gas landscape and decarbonization scenarios

Natural gas is a fossil fuel that is used intensively in various sectors of the global economy. Electric power generation is one of these sectors, accounting for a quarter of total generation. The infrastructure for storage, transportation (pipelines and ships) and liquefaction of natural gas is highly developed, which makes this fuel attractive. Likewise, power plants using this fuel serve as a backup for electricity generation from intermittent renewable sources such as wind and solar energy, due to their fast response time (IEA, 2024).

The combustion of natural gas generates less carbon dioxide (CO_2) emissions compared to combustion of coal or petroleum derivatives (EIA, 2024). However, it emits large amounts of methane (CH_4) during its production and handling, which is a potent greenhouse gas (GHG). This gas has a global warming potential (GWP), which is about 30 times greater than the same mass of CO_2 emissions over a 100-year time period; and more than 80 times more potent over a 20-year period. Methane is therefore the second largest contributor to climate change (World Bank, n.d.). The oil and gas industry is a major source of CH_4 emissions worldwide. In fact, methane emissions from venting, flaring and flaring in the oil and gas sector are currently estimated to be responsible for approximately 25% of global anthropogenic methane emissions (World Bank, n.d.).

As noted by the Intergovernmental Panel on Climate Change (IPCC), fugitive emissions from oil and natural gas systems are often difficult to quantify accurately. This is mainly due to the diversity of the sector, the large number and variety of potential emission sources, wide variations in emission control levels, and the limited availability of data on emission sources. Among the main sources of uncertainty are the use of simple and general factors, the difficulty of obtaining detailed data from installations, and problems in carrying out measurement campaigns due to their demands on human resources, time and costs (IPCC, 2006).

Because of this, in recent years it has become clear that the true magnitude of fugitive emissions in the oil and gas sector may be greater than currently estimated. Recent satellite and aircraft remote sensing techniques show divergences between inventories and estimates based on observations and collected data. For example, in the United States, a recently published study indicates that methane emissions in oil and gas may be three times higher than the official inventory. The estimates are based on about 1 million aerial measurements in major production regions (Stanford University, 2024). In the same vein, a review of methane emissions from the UK sector shows that they could be more than five times that reported in official sources. Estimation methods include measurements on board ships.

emissions from oil platforms (Center for Policy Research on Energy and the Environment, 2023). In the case of Mexico, Shen, et al. (2021) indicate that anthropogenic methane emissions in the eastern region of the country may be 45% higher than those estimated in inventories, based on analysis of satellite observations, while Zavala-Araiza, et al. (2021), point out, with the support of aerial measurements, that the national inventory of greenhouse gas emissions underestimates methane emissions by more than an order of magnitude in the terrestrial region, and similarly overestimates it in the marine region (Shen et al., 2021; Zavala-Araiza et al., 2021).

Currently, China has become a major importer of natural gas, which is why the country has turned to global LNG markets (IEA, 2023). This is why the increase in unconventional natural gas production in the United States and its positioning as a net exporter has increased its attractiveness in Asian markets. This increase in the use of natural gas as a fuel could affect the required decarbonization plans. In this regard, the IEA's global net-zero emissions scenarios show that, in order to achieve carbon neutralization, natural gas demand will need to decrease by 2050. Specifically for the Net Zero Emissions Scenario for 2050 (NZE), which points the way for the global energy sector to reach net zero CO_2 emissions by 2050, demand needs to be reduced by 2% per year between 2022 and 2030, and by almost 8% per year between 2030 and 2040. This means that the demand for natural gas in 2050 will be 919 billion cubic meters (m^3) (IEA, 2023).

To achieve the NZE, to the IEA (2023), in addition to reducing natural gas consumption, it will be necessary to increase the installation of wind and solar photovoltaic power generation projects. For the NZE Scenario, there is a need to install up to 350 GW of wind capacity internationally, and 820 GW of solar PV capacity (IEA, 2023).

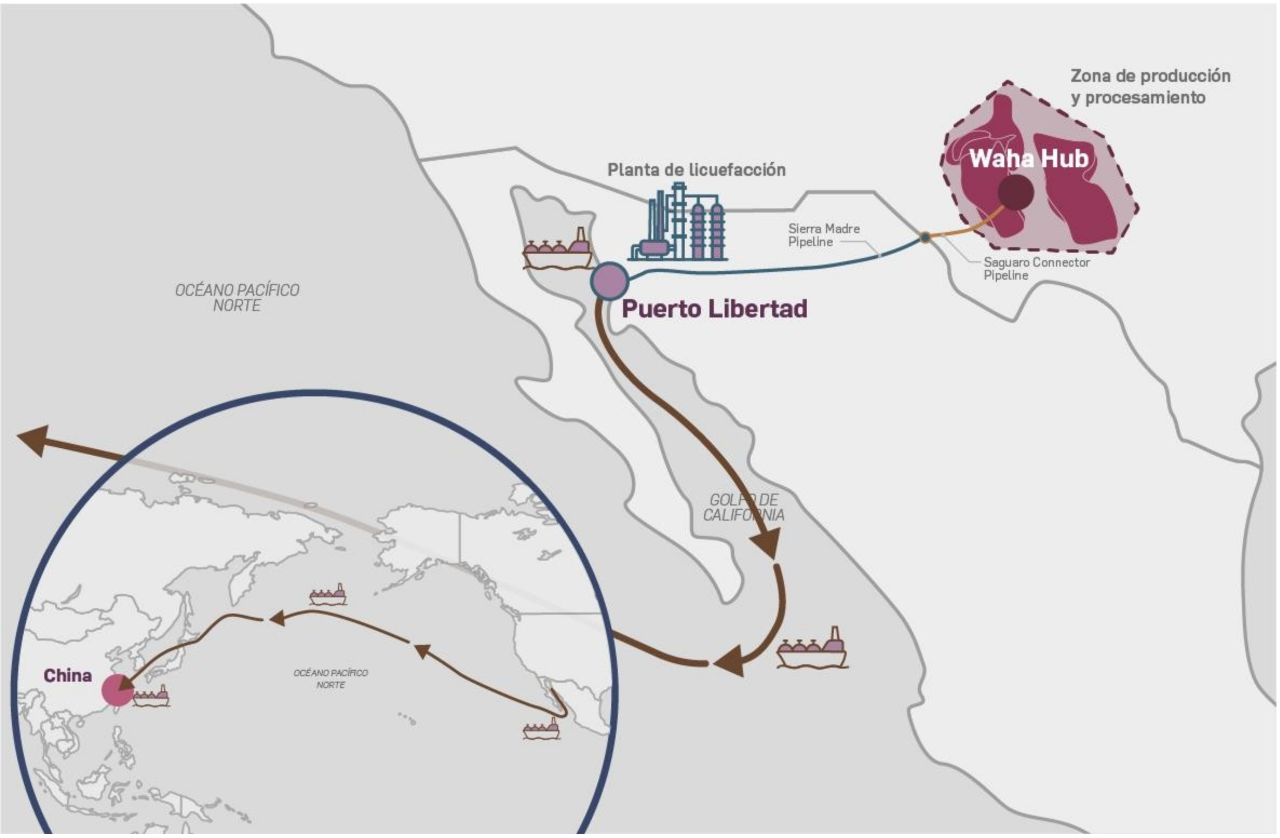
1.2. Natural gas and the Mexico Pacific Limited project: Saguaro Energía

In 2023, the United States became the largest exporter of LNG in the world. 66% of exports go to Europe, while 26% go to Asia (EIA, 2024). The expansion of natural gas demand in Asian markets has been seen as an opportunity to expand U.S. LNG exports to these markets. To this end, Mexico has been considered as an outlet for this natural gas. The U.S. Energy Information Administration (EIA) has estimated that by the end of 2027, the North American region will double its LNG export capacity, with the development of natural gas export infrastructure in Mexico and Canada (Alavez, 2023).

One of the projects being developed in Mexico is the natural gas liquefaction plant in Puerto Libertad, Sonora, which also seeks to build a pipeline connecting natural gas production in the United States with the plant and with the Asian market (Global Energy, 2024). This plant, which is also known as the Saguaro Energía project, seeks to process 15 million tons per year (Mtpa) of natural gas in three liquefaction trains. The owner, Mexico Pacific Limited, LLC, has indicated that it has plans to double this capacity in a second phase, to to reach an installed capacity of six trains that will process 30 Mtpa. Given the magnitude of the project, Mexico could become the fourth largest exporter of LNG worldwide (Bnamericas, 2024). In this analysis, a capacity of 15 Mtpa was considered, since this is the amount of gas currently authorized for processing; however, it should be noted that emissions from a project with double the capacity could approximately double.

The project will transport natural gas produced in the Permian Basin in the United States to the plant through existing cross-border pipelines between the United States and Mexico. These pipelines include an interstate natural gas pipeline owned by Sierrita Gas Pipeline LLC, and intrastate natural gas pipelines owned by Comanche Trail Pipeline, LLC, Roadrunner Gas Transmission, LLC and Trans Pecos Pipeline, LLC, all located in West Texas (Mexico Pacific Limited LLC, 2022). Also, the project includes the construction of a new gas pipeline called Sierra Madre, which will have a length of 800 km, 48 inches in diameter; having four compression stations, as well as a measurement, regulation and control station. This pipeline will be the main natural gas supply route from the border in the state of Chihuahua, Mexico and the United States to the LNG export plant in Puerto Libertad, Sonora. Finally, this natural gas will be used in Asia, for which there are already several contracts with energy companies (Mexico Pacific Limited LLC., 2024a). The following figure shows the trajectory that the natural gas will follow.

Figure 1. Project map.



1.3. Mexico's Climate Change Commitments

In 2016, Mexico ratified the Paris Agreement on Climate Change along with 175 other member countries of the United Nations (Presidency of the Republic, 2016). This Agreement seeks to limit the global average temperature increase to less than 2°C, with the goal of not exceeding 1.5°C. The Agreement is legally binding, universal in nature, and establishes long-term goals, whose fulfillment is based on clear commitments, both in mitigation and adaptation (INECC, 2021). To this end, the signatory countries must submit their GHG emission contributions, known as Nationally Determined Contributions (NDCs), on a five-yearly basis. These contributions must be increasingly ambitious (IMCO, 2016).

Mexico's last update of its NDCs was in 2022 during the 27th Conference of the Parties (COP). At this event, an increase in emissions reduction target from 22% to 35% by 2030 was announced (SEMARNAT and INECC, 2022; IMCO, 2022). With respect to the oil and gas sector, a 14% emissions reduction target was established (SEMARNAT and INECC, 2022). This is complemented by the Global Methane Commitment, to which Mexico adhered in 2021. This Commitment was promoted by the United States and the European Union, with the aim of reducing global anthropogenic methane emissions in 2030 by 30% below the levels recorded in 2020 (SRE, 2021).

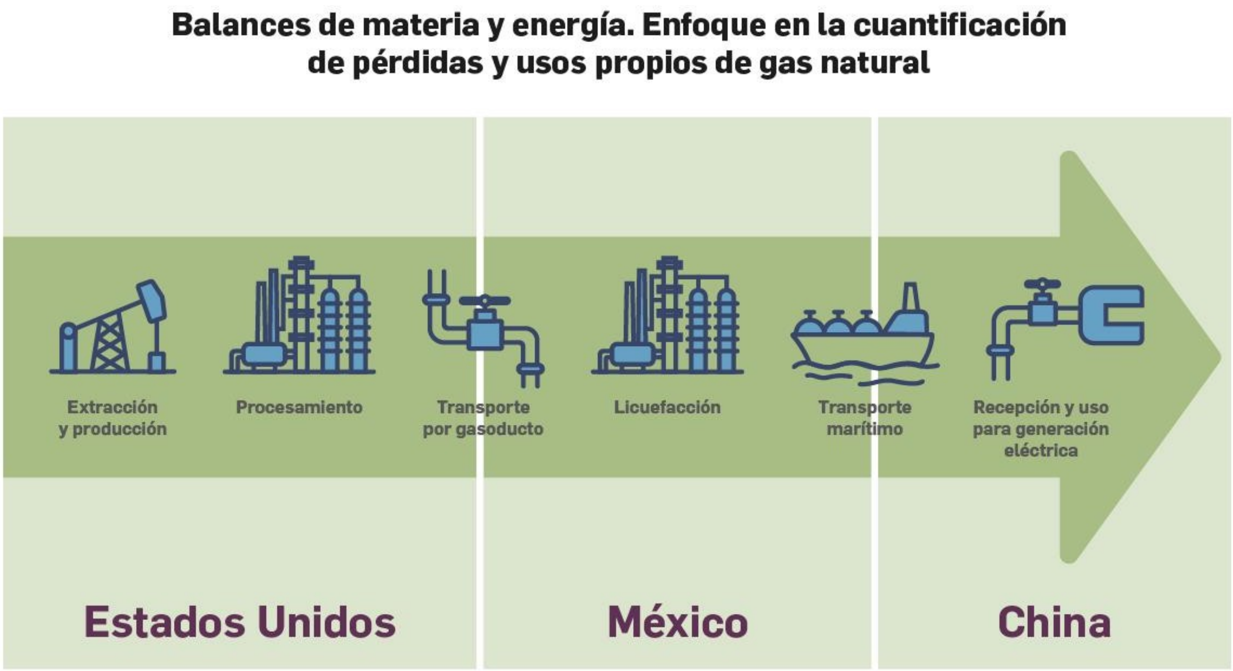
Although there is no commitment by the country to achieve net emissions by 2050, the Mexico Climate Initiative (ICM) has developed a proposal for Mexico called Zero Net Emissions from Civil Society. This proposal considers the oil and gas sector as strategic for the mitigation of GHG emissions in Mexico with an emissions reduction potential of 24 $MtCO_2e$ in 2060 (ICM, 2023).

In the case of the project analyzed in this paper, there is no evidence that Mexico has conducted a study of its GHG emissions or its impact on the country's mitigation goals contained in the NDC. Therefore, this analysis is presented below.

2. Objective and scope

The objective of the work presented in this report was to estimate the greenhouse gas (GHG) emissions of the natural gas extraction and production chain in the United States (specifically in the Permian Basin), as well as its transportation to Mexico, through a gas pipeline; its liquefaction in Puerto Libertad (state of Sonora), its maritime transportation to Asia (China) and its use for the generation of electric energy in this last point.

Figure 2. Flow diagram of the system to be analyzed.



3. Methodology

As ISO 14044:2006 points out, awareness of the importance of protecting the environment and the potential impacts of the products and services generated by mankind has been growing. In order to understand these impacts in greater detail, methodologies have been developed for their quantification. Life cycle analysis (LCA) represents one of these methodologies and was developed by the International Organization for Standardization (ISO). The work contained in this report was carried out following this methodology, which basically consists of the following steps (BSI, 2020).

1) Definition of the objective and scope of the LCA.
2) The cycle inventory analysis phase.
3) The cycle impact analysis phase.
4) The interpretation phase of the cycle.
5) The LCA report and critical review.
6) The relationship between the phases of the LCA.
7) Conditions for the selection of the values used and the optimal elements.

It is important to note that this methodology can support the assessment of various environmental impacts such as acidification, photochemical ozone formation, and the emission of ozone depleting compounds, among others. However, the work presented here is limited to the estimation of greenhouse gas (GHG) emissions and their impact on climate change. For this purpose, the GHGs quantified, due to their importance, include carbon dioxide (CO_2) and methane (CH_4).

3.1. Limitations of the methodology

It is important to note that the estimation of the carbon for this work was carried out based on existing information in the literature. As will be presented in the corresponding sections, average values have been used for the estimation, as well as typical values. This generates uncertainty in the calculations. Likewise, there is a limitation with respect to the information available for the project, so assumptions have been made. Shipping and LNG end-use are examples of the above, so estimates have been based on the most publicly available information. A detailed analysis by the stakeholders involved in the project could be very useful to understand the impact of the project along its entire chain. It is important to emphasize that this study does not consider emissions during the construction or dismantling phase of the facilities, nor emissions of compounds that could have other environmental impacts. The study is limited to the estimation of the carbon footprint for the routine operation of the system.

4. Estimation of GHG emissions

4.1. Natural gas production, gathering, processing and transportation in the United States

For the estimation of emissions from the natural gas production chain in the United States, the emission intensities of the greenhouse gases considered (carbon dioxide, CO_2 and methane, CH_4) were determined for each stage of the applicable chain (production and storage, processing and transportation by pipeline to the Mexican border). This was done based on each unit of dry gas passing through each stage in . The flow of dry gas at each stage was determined based on the gas available at the border that will be transported into Mexican territory, the gas losses as a result of its use as fuel for transportation, and the quantities of gas emitted due to leaks and venting. These losses were quantified as a fraction of dry gas in relation to the total dry gas entering each stage. In this way, the gas flow through the chain was reconstructed by adding these losses to the input of each stage. For each stage, the emission intensities and losses were estimated with information from various sources, which are explained in more detail in the corresponding section. This methodology is similar to that reported in Zhu, et al. (2024) and Vallejo, et al. (2023). In the stages of production and gathering, and processing, there are different products (direct production gas, condensates and crude oil in the production part, dry gas and natural gas liquids in processing). The gas balance considers only the final product (dry gas). The dry gas flows were determined considering the characteristics of the products at each stage (volume, composition and energy content). Table 1 shows the general calculation parameters used. The main parameters per stage are shown in the corresponding sections.

Table 1. Main calculation parameters for natural gas production, storage, processing and transportation.

General parameters	
Diesel (LHV) Btu/gal) (The Engineering ToolBox, 2003)	**129,306**
Diesel density (t/barrel) (The Engineering ToolBox, 2003)	**0.13**
FE diesel (gCO_2/MJ) EIA, 2023)	**74**
LHV methane (MJ/kg) The Engineering ToolBox, 2003)	**50**
Methane density ($kgCH_4/m^3CH_4$) Zhu, et al., 2024)	**0.657**
FE natural gas combustion (gCO_2/MJ) (EIA, 2023)	**55.7211083**
Permian Basin Data	
LHV crude oil MMBtu/barrel) Rosselot, et al., 2021)	**5.32**
LHV produced gas (Btu/scf) Plant, et al., 2024)	**1,173**

LHV dry gas (Btu/scf) Contreras, et al., 2021)	**884**
Fraction (on energy basis) corresponding to dry gas with respect to total products in production stage (Zhu, et al., 2024).	**0.31**
Fraction (on energy basis) corresponding to dry gas in produced gas, processing (Zhu, et al., 2024).	**0.745**
Percentage of methane in dry gas (molar) (Contreras, et al., 2021)	**0.97**
Dry gas density (kg/scf) (Contreras, et al., 2021)	**0.01968**
Methane mass fraction in dry gas (Contreras, et al., 2021)	**0.95**

Note: LHV: Low heating value; FE: Emission factor; Produced gas: natural gas before ; scf: standard cubic foot; gal: gallon; t: ton; MJ: Mega Joule; MMBtu: million Btu.

For the allocation of emissions in the production and gathering stages, as well as in processing, the criteria outlined in the work of Roman-White, et al. (2021) were considered, which in turn are based on the guidelines of the ONE Future Methane Emissions Estimation Protocol, and the Natural Gas Sustainability Initiative (NGSI) methane emissions intensity estimation protocol (ONE Future, 2023; M.J. Bradley & Associates-ERM Group company, 2021). The allocation was made based on the energy content of the natural gas relative to the products of each stage.

4.1.1. Production

The production stage comprises the activities necessary for the extraction of hydrocarbons. It can be divided into two main parts; during pre-production, the preparation of the facilities that will be used in the exploitation of the reservoir is carried out. This includes the drilling of the wells, through the use of special drilling machines, the installation of pipes inside the drilled holes and their cementing. Subsequently, it continues with the completion, which to create channels or conduits to communicate the reservoir resource with the main borehole. In the case of unconventional reservoirs, hydraulic fracturing techniques are used for this purpose. Subsequently, there is the production stage itself, where activities are oriented to the extraction of the hydrocarbon and to maintain production over time. The gas that is extracted is collected from multiple wells to be sent to gas processing centers, or to enter directly to the transmission stage if the characteristics of this gas are appropriate for its commercialization. This gathering and collection stage is out with the use of various equipment and facilities such as pipeline systems, compressors and temporary storage terminals.

For the life cycle analysis of the project's GHG emissions, it was assumed that all of the gas to be exported to Mexico comes from the Permian Basin. This assumption is based on information from various sources, such as documents submitted by Mexico Pacific Limited (MPL) to the U.S. Department of Energy (DOE).

The U.S. Department of Energy (DOE), as well as plans to develop gas transportation infrastructure in Mexican and U.S. territory, connecting the liquefaction plant with the natural gas interconnection and commercialization zone known as the Waha Hub, located in Texas, within the Permian Basin (U.S. DOE, 2024; Transportadora de Gas Sierra Madre, 2023; Global Energy Monitor, 2024).

The estimation of emissions in production also includes emissions in the gathering and collection stage. This was considered in this way with the intention of including CH_4 emissions data from satellite observations in the estimation, which include the production and collection stages, given the proximity of the facilities of one and the other.

The estimated emissions categories include pre-production emissions, emissions from the use of fuels for gas compression and dehydration, emissions in the acid gas removal process, emissions from flaring at the facilities, and fugitive methane emissions in the production, storage and collection systems. The latter include all emissions from venting, leaks and incomplete flaring.

The pre-production stage includes emissions from the use of diesel in equipment, for well drilling and hydraulic fracturing, as well as those derived from the handling and transportation of water used in fracturing (Mallapragada, et al., 2018). Given that these activities are only performed once throughout the useful life of the wells, it is necessary to divide the resulting emissions by the annual estimate of the total potential hydrocarbon production of each well during the time it is in production. This estimate is known as EUR (Estimated Ultimate Recovery). In this way, emissions can be expressed per unit of hydrocarbon produced per year. In the Permian Basin crude oil and natural gas are produced, so the value of this variable includes both, in units of energy (MJ). Consequently, emissions from these activities are the result of the production of both crude oil and gas, so it is necessary to allocate the portion corresponding to gas. The allocation of emissions was carried out according to the energy of the products of the stage, specifically, of the fraction in energy terms corresponding to dry gas. The fuel consumption data and others related to the pre-production activities considered were taken from information for the Marcellus Basin, in the Appalachian region, due to the lack of data for the Permian Basin, in addition to the fact that it is assumed that, due to the characteristics of the type of hydrocarbons exploited, the pre-production activities are similar (Zhu, et al., 2024). The estimated emissions correspond to CO_2 derived from diesel combustion. The following table shows the main calculation parameters considered.

Table 2. Main parameters used for estimates in the production stage.

Parameters	Values
Drilling diesel usage (gal/well) (Mallapragada, et al., 2018).	**16,952**
Diesel use hydraulic fracturing (gal/well) (Mallapragada, et al., 2018).	**41,235**

Diesel use to transport waste water (Btu/t/mile) (Stanford University, 2017).	**969**
Hydraulic fracturing water use (barrels/well) (Mallapragada, et al., 2018).	**245,293**
Distance from well to final water disposal (miles) (Laurenzi & Jersey, 2013)	**352**
Permian Basin Data	
Estimated ultimate recovery (EUR) of gas Thousands scf per well per year) (Littlefield, et al., 2019).	**13,600,000**
Estimated ultimate recovery (EUR) of crude oil (barrels/well/year) (Littlefield, et al., 2019).	**1,670,000**

For the estimation of CO_2 emissions from the use of natural gas in compression and dehydration, as well as those derived from flaring and acid gas removal, emission factors developed by the U.S. National Energy Technology Laboratory (NETL) in its 2019 study were used, adjusted to represent emissions as a function of gas flow in the stage (Zhu, et al., 2024; Littlefield, et al., 2019). Emissions from acid gas removal are process emissions, so there are no gas usage losses, so they are not considered in the overall natural gas balance. The factors reported in the NETL study have already assigned emissions to natural gas. The following table shows the values considered (Zhu, et al., 2024).

CO_2 emission factors for the production stage.

Emission factors	Values
CO_2 emissions intensity using natural gas for compression (gCO_2/MJ gas)	**1.8863**
Intensity of CO_2 emissions using natural gas for dehydration (gCO_2/MJ gas)	**0.3983**
CO_2 emissions intensity by acid gas removal process (gCO_2/MJ gas)	**0.0121**
Intensity of CO_2 emissions from flaring (gCO_2/MJ gas)	**0.0602**

For the quantification of CH_4 emissions, information derived from satellite observations in the Permian Basin, originally reported in Zhang, et al. (2020), was used. The emission rate reported by the authors is 3.7% of the total gas produced in the area. The emission rate value used was 3.52%, which is an estimate for the production and gathering stages according to Zhu, et al. (2024), based on emission proportions from oil and gas facilities participating in the U.S. Environmental Protection Agency (EPA) emissions reporting program (GHGRP). The resulting methane emissions were assigned to dry gas based on the energy fraction of the stage products (crude oil, condensate and gas).

4.1.2. Processing

In the processing stage, the gas coming from the production fields goes through a series of processes whose final objective is to prepare it to acquire adequate characteristics for its final commercialization. Broadly speaking, this involves the removal of various impurities such as water, carbon dioxide, solid particles, sulfur, heavy hydrocarbons and nitrogen, among others. The types of processes used can be conditioning, separation, or fractionation, and for there are different technologies. The final gas obtained contains high percentages of methane (generally greater than 90% by volume), and is known as dry gas, which is sent to the transportation system to take it to the points of consumption.

For this stage, CO_2 emissions from fuel use in the processing plant, combustion emissions from flaring, and process CO_2 emissions from acid gas removal were estimated. Data for the estimates correspond to typical U.S. average values derived from the GHGRP for 2018 (U.S. EPA, 2018; Roman-White, et al., 2021). As with all stages, losses of gas used as fuel, flared or emitted to the atmosphere from leaks or venting were identified to make the natural gas balance. For emissions from acid gas removal, average emissions per plant in the United States as reported in the references were considered. The allocation of emissions in the stage was carried out based on the energy of the dry gas with respect to the energy of the output products (process condensates, dry gas and natural gas liquids), and was applied to emissions from flaring. For acid gas removal and compressor fuel use, all emissions are attributed to gas. The following table shows the relevant parameters used.

Relevant parameters considered in the processing stage.

Parameters	Values
Gas to flaring (flaring, scf) (Zhu, et al., 2024)	**174,000,000**
Burning efficiency (Zhu, et al., 2024)	**98%**
Produced natural gas entering processing plant Millions of scf/yr) (U.S. EPA, 2018)	**36,900,000**
Energy used in centrifugal compressors in processing facility (hp-h) (Roman-White, et al., 2021)	**54,500,000**
Energy used in reciprocating compressors in processing (hp-h) (Roman-White, et al., 2021).	**92,400,000**
Emissions in acid gas stripping units in processing plant (tCO_2) (Roman-White, et al., 2021)	**24,600**

Note: hp-h: horsepower-hour, horsepower-hour.

CH_4 emissions were estimated similarly to the production and gathering stage, with data derived from satellite observations from Zhang, et al. (2020). At the processing stage, the CH_4 emission rate estimated in Zhu, et al. (2024) is 0.185% over total gas production. The CH_4 emissions were assigned to the dry gas based on the energy fraction in the gas entering the stage prior to treatment at the processing plant.

4.2. Pipeline transportation in the United States

For the transportation stage in the United States it is considered, as described above, that the natural gas to be used in the export project comes from the Permian Basin. The transmission distance is estimated as the average between the distance between gas processing centers in the northern Pecos and Midland area in Texas (EIA, 2024) to the interconnection at the Waha Hub. This distance follows the transmission pipeline routing consulted in the U.S. Department of Transportation (U.S. DOT) maps, with data from EIA (U.S. DOT, 2024). From this point, it is assumed that natural gas will be transported to the Mexican border through the Saguaro Connector Pipeline, which is being constructed by Saguaro Connector Pipeline, LLC, a subsidiary of ONEOK. This will be a pipeline that will cross part of Texas, connecting the Waha Hub with the Mexican border, and in turn, will connect with the Sierra Madre pipeline, which will carry natural gas to the liquefaction plant (Global Energy Monitor, 2024). Accordingly, the total distance considers 143 km from the processing centers to the Waha Hub, as well as the 250 km of the Saguaro pipeline, for a total distance of 393 km.

Estimated CO_2 emissions correspond to gas burned as fuel in compressor stations. In the case of CH_4, emissions from incomplete combustion, fugitive emissions in gas pipelines and compressor stations, and emissions from venting in facilities related to gas pipelines, in pneumatic control devices and in the compressor stations themselves were estimated. For the estimation of both CO_2 and CH_4 emissions, information reported in the literature was used, which presents average values for facilities in the United States, mainly from the studies of Zimmerle, et al. (2015), from EPA GHGRP data and from the NETL study regarding the life cycle emissions analysis of the natural gas chain. From this and subsequent steps, all emissions are attributed to natural gas. The main parameters used are shown in Table 5.

Parameters used for estimating emissions from transportation in the United States.

Parameters	Values
Distance between compressor stations (km) Penn State Extension, 2015).	**88.5139**
Transmission distance (km)	**393**
Percentage of reciprocating compressor stations (Zimmerle, et al., 2015).	**77%**
Percentage centrifugal compressor stations (Zimmerle, et al., 2015).	**23%**
Capacity reciprocating stations (hp) (Zimmerle, et al., 2015).	**10,942**
Capacity centrifugal stations (hp) (Zimmerle, et al., 2015).	**18,988**
Annual hours of operation reciprocating stations Zimmerle, et al., 2015).	**2,890**
Annual hours of operation centrifugal stations Zimmerle, et al., 2015).	**2,587**
Thermal efficiency reciprocating machine (Littlefield, et al., 2019).	**44%**
Thermal efficiency centrifugal turbine (Littlefield, et al., 2019).	**26%**
Natural gas output performance Mcf/facility/year) Roman-White, et al., 2019).	**124,000,000**
Fugitive CH_4 emissions factor transmission stations ($MgCH_4$/station) (Zimmerle, et al., 2015).	**64**
Fugitive CH_4 emissions factor reciprocating compressors ($MgCH_4$/compressor) (Zimmerle, et al., 2015).	**64**
Fugitive CH_4 emissions factor centrifugal compressors ($MgCH_4$/compressor) (Zimmerle, et al., 2015).	**54.5**
Non-categorized fugitive emissions factor $MgCH_4$/station) Zimmerle, et al., 2015).	**200**
Incomplete combustion emission factor for reciprocating stations CH_4 (gCH_4/hp*h) (Zhu, et al., 2024)	**3.7**
Incomplete combustion emission factor for centrifugal stations CH_4 (gCH_4/hp*h) Zhu, et al., 2024)	**0.031**
Fugitive emission rate pipelines ($kgCH_4$/mile) Roman-White, et al., 2021)	**1,120**
Quantity of gas transported in pipelines (Millions of cubic feet/facility/year) (Roman-White, et al., 2021)	**1,350,000,000**
Emission rate pneumatic venting devices ($MgCH_4$/device) Zimmerle, et al., 2015).	**1**
Number of pneumatic devices (Zhu, et al., 2024)	**16**
Emission rate venting transmission stations ($MgCH_4$/station) Zimmerle, et al., 2015).	**57**
Pipeline venting (tCH_4/year per 10,100 miles of pipelines) Roman-White, et al., 2021)	**3,810**

4.3. Natural gas transportation and liquefaction in Mexico

4.3.1. Pipeline transportation in Mexico

For the estimation of CO_2 and CH_4 emissions, the information available in the Environmental Impact Statement (MIA) for the Sierra Madre gas pipeline (Transportadora de Gas Sierra Madre, 2023) was considered. Fugitive and venting emissions were calculated, as well as CO_2 emissions from natural gas to meet the energy needs of the compressor stations. This pipeline has four compressor stations with turbogenerators with a total installed capacity of 23.8 MW. The pipeline also has a metering station. A typical efficiency of 35% was considered for the turbogenerators. The gas balance was estimated considering fugitive and venting emissions, as well as the fuel needs of the turbogenerators. The emission factors considered are presented in INECC (2012). The following table summarizes these values.

Emission factors for the natural gas transportation stage in Mexico.

Vent emission factors		
Venting (Gg of CH_4/Million m^3 of gas transported) (INECC,	2012)	**0.00032**
Venting (Gg of CO_2/Million m^3 of gas transported) (INECC,	2012)	**0.0000031**
Fugitive emission factors		
Fugitive transport (Gg CH_4/Million m^3 of gas transported)	INECC, 2012)	**0.00048**
Compression (Gg of CH_4/MW installed) (INECC, 2012)		**0.015**
Measuring stations (Gg of CH_4/facility) INECC, 2012).		**0.00375**
Fugitive transport (Gg of CO_2/Million m^3 of transported gas$^{)}$	(INECC, 2012)	**0.00000088**
Compression (Gg of CO_2/MW installed) (INECC, 2012)		**0.0000275**
Measuring stations (Gg of $_{CO_2/facility}$) (INECC, 2012)		**0.00000688**

4.3.2. Natural gas liquefaction

The estimation of CO_2 and CH_4 emissions for the liquefaction of natural gas at the plant located in Puerto Libertad took into account the process to be used, which corresponds to the optimized ConocoPhillips cascade process. This process is based on three multi-stage cascade refrigeration circuits using pure refrigerants (methane, propane and ethylene). It also consists of heat exchangers built in welded aluminum in insulated cold boxes, in which a high thermal integration is achieved (ConocoPhillips, 2024).

According to the company's plans, the plant will be built in two stages, which will have a total installed liquefaction capacity of 30 million tons of natural gas. In the first stage

3 liquefaction trains will be built with an installed capacity of 15 million tons of natural gas (Bnamericas, 2024). Based on this information, the natural gas balance and GHG emissions were estimated. For this, the information presented by Howarth (2024) was considered with respect to the unburned CH_4 emission factors (0.11 g of CH_4/kg of LNG), as well as the CO_2 emissions from combustion to cover the plant's energy requirements (230 g of CO_2/kg of LNG), and the CO_2 contained in the gas (23 g of CO_2/kg of LNG). It is important to note that, the aforementioned values correspond to low values of the range proposed by Howarth (2024), based on the work of Balcombe (2011), Tamura et al. (2001) and Okamura et al. (2007). This information was reviewed and contrasted with respect to existing information from a plant with the same liquefaction process in Corpus Christi (USA). According to information provided by the U.S. Energy Information Agency (EIA) and the U.S Environmental Protection Agency (EPA), emission factor for the plant 226 g CO_2e per kg LNG nominal capacity. This value is close to the low value reported by Howarth (2024), so these values were used. From the CO_2e emissions from combustion, the natural gas required to meet the plant's energy needs was estimated. Considering this and the emissions of unburned CH_4, the natural gas used to carry out the liquefaction process of the LNG itself is 0.08 kg of natural gas per kilogram of liquefied natural gas produced.

4.4. Shipping to Asia

The amount of natural gas transported by sea corresponds to 912,220 MMscf (million standard cubic feet), which were obtained from the permits granted by the DOE to the project developer (Mexico Pacific Limited LLC., 2022). To determine the natural gas balance at this stage, it was considered that natural gas is used as fuel for the vessel, in addition to the fact that there are losses from unburned natural gas. The determination of these quantities depends largely on the type of vessel used. The Environmental Impact Assessment (EIA) for the project mentions that the dock will be designed to receive vessels with an average regular cargo volume of 135,000 m^3 of liquefied natural gas (LNG). The dock will be able to receive vessels with a cargo volume ranging from 71,500 m^3 to 265,000 m^3 of both spherical and membrane type (HP Consultores Ambientales, 2006).

An analysis of the existing international LNG carrier fleet was carried out to determine a typical vessel size for the estimates. For this purpose, the above-mentioned average regular cargo volume and available information on global maritime traffic with respect to the types of LNG-carrying vessels obtained from VesselFinder (2024) and MarineTraffic (2024) were considered. It was found that 57% of LNG carriers with a capacity between 135,000 m^3 and 162,000 m^3 of LNG use both LNG and fuel oil for propulsion. Also, all of these vessels are vessels. Unlike these vessels, the more modern ships are based on two- and four-stroke engines that use evaporating natural gas as fuel.

Although the first type of vessel (steamship) was considered for the estimation, estimates were made for the last two types of vessels because they correspond to vessels with more recent technology and that have a more recent technology.

may dominate the market in the future. However, the details of the calculations for the latter two ship types are presented in the Annexes section. The estimates were based on emission factors provided by Howarth (2024), which mainly take the work of Balcombe, Heggo and Harrison (2022). Recently, the International Council on Clean Transportation (ICCT) conducted a study to estimate the amount of methane released for different types of vessels using LNG, including LNG carriers (Comer, 2024). The results were consistent with the work of Balcombe, Heggo and Harrison (2022), so the methodology of Howarth (2024) was used. Based on this methodology, it was estimated that 295 trips (round trip) are required to transport all the LNG, bringing the total to 590.

Emission factors for the transport of LNG in steam-powered ships.

Emission factors fuel combustion	
Steamship burnup (gCO_2/kgGNL) Raza and Schoyen Ziomas, , 2014; Bakkali and 2019).	**262.734**
Fuel oil combustion (gCO_2/kgGNL)	**291.371**

4.5. Use of natural gas for power generation in Asia

LNG will be used in the Asian markets, and the available information on its possible uses was reviewed. There are several companies that have signed contracts to acquire this LNG, including ExxonMobil (3.4 million tons of LNG per year, Mt of LNG), Shell (3.7 Mt of LNG), ConocoPhillips (2.2 Mt of LNG), Zhejiang Energy (1.0 Mt of LNG), Guangzhou Development Group (2.0 Mt of LNG), and Woodside Energy (2.0 Mt of LNG) (Mexico Pacific Limited LLC, 2024a). So far there is no definite information regarding the use of LNG, and it is possible that this natural gas is mixed with natural gas coming from other places; therefore, the carbon footprint was quantified up to the point of entry to the use of the gas. In this work, it was assumed that LNG would be used for electric power generation through natural gas combined cycle (CC) or natural gas open cycle (TG). Table 8 presents the assumptions considered in the electric generation that were taken from Rosselot, et al. (2021). For this stage, the regasification of LNG for transportation to the power plant was considered. In the regasification stage, CH_4 emissions of 0.018% of the regasified natural gas were considered (Innocenti, et al., 2023). Finally, for electricity generation, emission factors proposed by Rosselot, et al. (2021) were used.

Table 8. Assumptions considered in electricity generation.

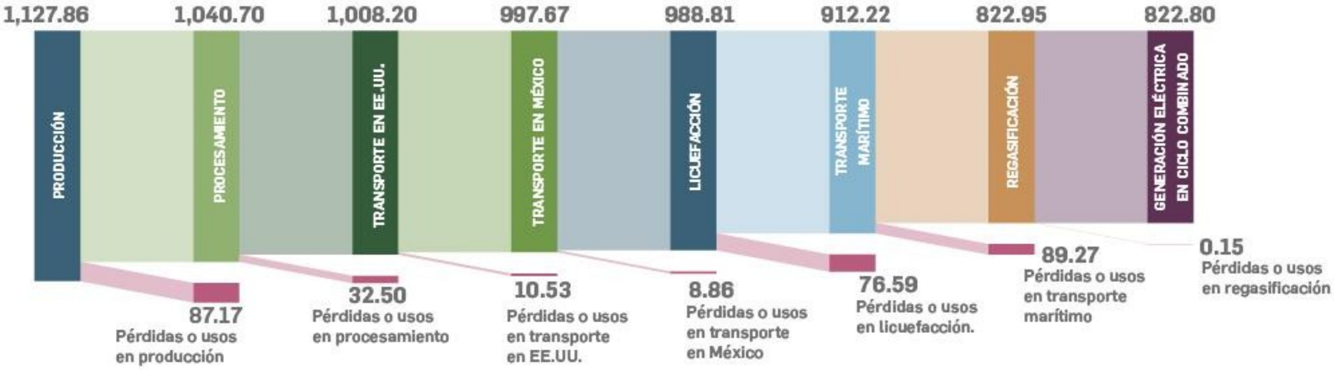
Combined cycle	
Emission factor (kgCO_2/MWh)	**440.0**
Amount of natural gas kg natural gas/MWh)	**160.4**
Thermal regime of the plant (kJ/MWh)	**7601.6**
Amount of unburned CH_4 (kg CH_4/MWh)	**3.9E-05**
Gas turbine	
Emission factor (kgCO_2/MWh)	**623.0**
Quantity of natural gas (kg natural gas/MWh)	**227.1**
Thermal rate of the power plant (kJ/kWh)	**10763.2**
Amount of natural gas per CH_4 not flared (kg natural gas/MWh)	**5.5E-05**
Emission factor (kgCO_2/kg natural gas)	**2.74**
Emission factor (kgCH_4/kg natural gas)	**2.4E-07**

Note: The emission factor per kg of natural gas for both cases is the same, because it corresponds to the emissions from the combustion of the same natural gas. However, the amount of gas used by the different power generation technologies depends on their conversion efficiency and therefore the emissions per MWh are different.

5. Natural gas balance

In the case of the natural gas balance, it was considered that the plant would deliver for marine transportation 912,220 MMscf, as mentioned (Mexico Pacific Limited LLC., 2022). From this information, and the CH_4 emission factors and the amount of natural gas used for power generation for each stage of the system, the natural gas balance along the entire chain up to the point of natural gas delivery to the power plants was estimated. The following figure presents the results for this balance considering that maritime transportation is carried out with steam propulsion vessels. It is important to mention that three estimates were made considering different types of vessels (steam, 4-stroke and 2-stroke). However, for the last two cases, the results are presented in the Annexes .section

Figure 3. Natural gas balance for the steamship case (Billions of standard cubic feet).



6. Life cycle GHG emissions

Based on the natural gas balance information and the emission factors presented in the previous sections, the following table presents the emissions for each of the stages of the system. For the case of the steamship, total emissions without taking into account the use of natural gas were 28.5 million tons of CO_2e per year (MtCO_2e). The use of fuel oil in maritime transport steamships contributes significantly to CO_2e emissions. In the case of Mexico, the project would generate 5.4 MtCO_2e in the national territory, which represents 1% of the country's 2019 net emissions, and almost 8% of Petróleos Mexicanos (PEMEX) direct emissions in 2022 (PEMEX, 2024).

Table 9. GHG emissions by stage for the case of transportation with steam-powered ships.

Stage	**CO_2 (tons/year)**	**CH_4 (tons/year)**	**CO_2e (PCG100) (tons per year)**
Natural gas production and storage	**2,507,710**	**224,465**	**9,196,767**
Natural gas processing	**2,042,902**	**25,918**	**2,815,252**
Natural gas transportation in the United States	**492,004**	**19,771**	**1,081,183**
Natural gas transportation in Mexico	**107,654**	**22,756.90**	**785,810**
Liquefaction	**4,542,024**	**1,974.79**	**4,600,873**
Maritime transportation	**9,947,658**		**9,947,658**
Regasification combined cycle		**2,915.24**	**86,874**
Regasification gas turbine		**2,915.24**	**86,874**
Use for combined cycle	**44,419,305**	**3.93**	**44,419,422**
Use for gas turbine	**44,419,305**	**3.93**	**44,419,422**
Total (combined cycle)	**64,059,257**	**300,720**	**73,020,714**
Total (gas turbine)	**64,059,257**	**300,720**	**73,020,714**

If the use of natural gas for power generation is considered, CO_2e emissions reach to 73.0 MtCO_2e. Emissions from the use of LNG represent more than 61% of total emissions.

It is important to mention that the functional unit defined in the work corresponds to one ton of natural gas delivered to the power plant. Therefore, the carbon footprint refers to

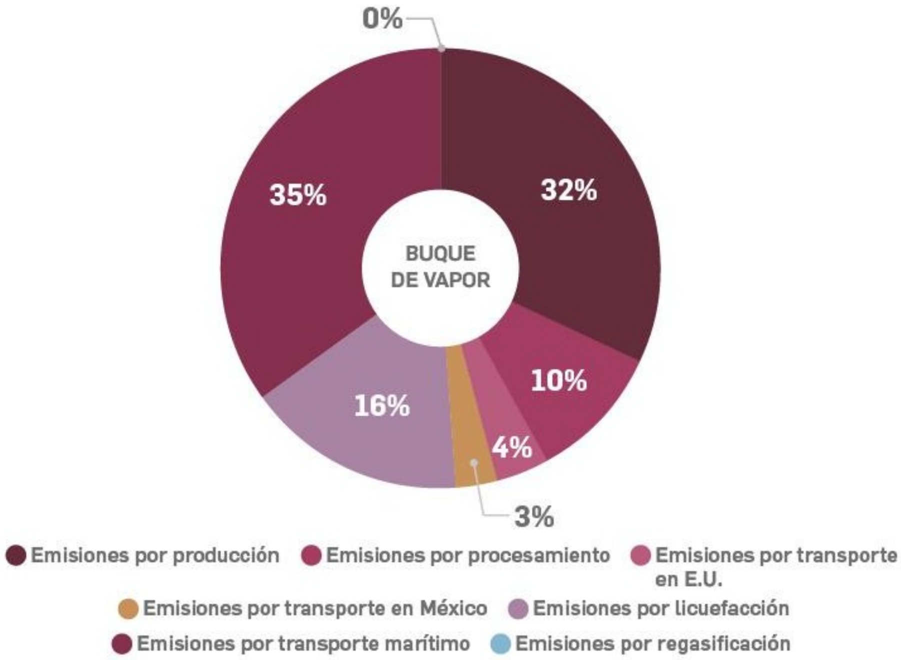
This functional unit and the stage for the use of this gas has not been included. Table 10 presents the carbon foot. The use of fuel oil in maritime transportation has a significant impact on GHG emissions.

Table 10. Carbon footprint for the steamship case.

Stage	Carbon footprint (tCO_2e per year/t of LNG delivered for use)
Footprint per production (natural gas)	**0.567952**
Footprint by processing	**0.173858**
U.S. transportation footprint	**0.066769**
Footprint by transportation in Mexico	**0.048528**
Liquefaction footprint	**0.284130**
Footprint from maritime transport (natural gas)	**0.614324**
Regasification footprint	**0.005365**
Total footprint	**1.761**

As shown in Figure 4, most of the carbon footprint of natural gas delivered corresponds to the natural gas production and processing stages in the United States. These two stages account for 42% of the carbon footprint. Production corresponds to the stage with the largest carbon footprint. The carbon footprint for transportation in the United States and Mexico around 10%. Finally, the carbon footprint for regasification is smaller than the other stages, so its contribution to the total carbon footprint is less than 1%.

Figure 4. Carbon footprint distribution.

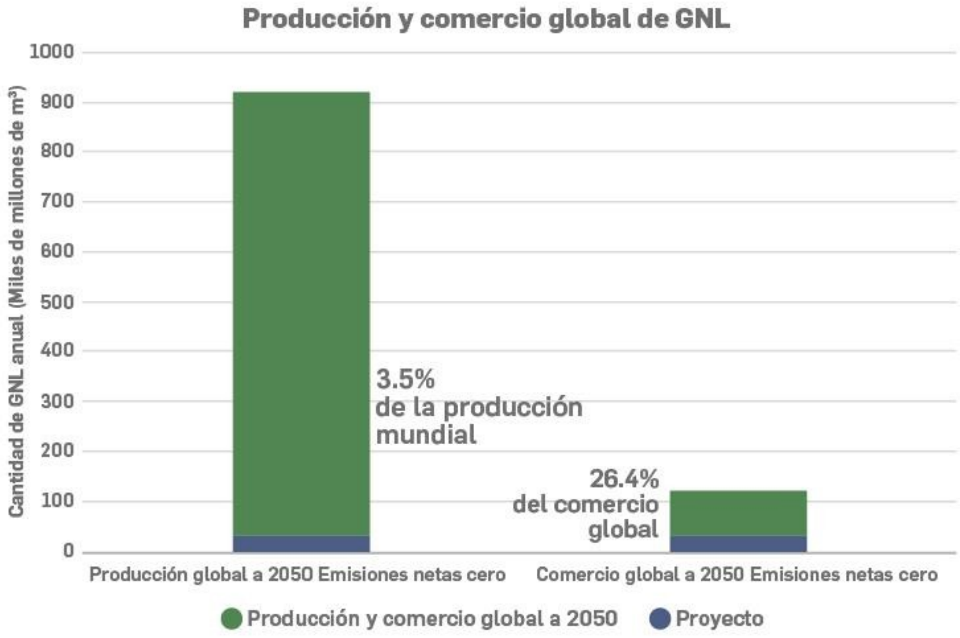


7. Mexico's LNG export project and its impact on climate change mitigation efforts

Natural gas has been considered for several years as a transition fuel. However, the problem of climate change and the reduction of greenhouse gas emissions requires urgent action to decouple economic activities from dependence on fossil fuels. In this sense, investment in assets that continue to favor the use of fossil fuels such as natural gas goes against the climate urgency, in addition to opposing the global goal of achieving net zero emissions by 2050. The project analyzed in this paper could represent a barrier to climate efforts not only globally, but also in Mexico.

In the global case, and as presented at the beginning of this document, the International Energy Agency (IEA) has established scenarios that indicate the need to limit world production and use of natural gas to 919 billion m^3 in order to achieve net zero emissions by 2050 (IEA, 2023). The Puerto Libertad project represents a production of 32 billion m^3 of natural gas per year, which is equivalent to 3.5% of that production in 2050. Likewise, in the case of LNG trade, the IEA's net zero emissions scenario points to an international trade of 121 billion m^3 by 2050. The project will account for 26.4% of this trade (see Figure 5).

Figure 5. Global LNG production and trade to 2050 in the IEA net-zero emissions scenario.

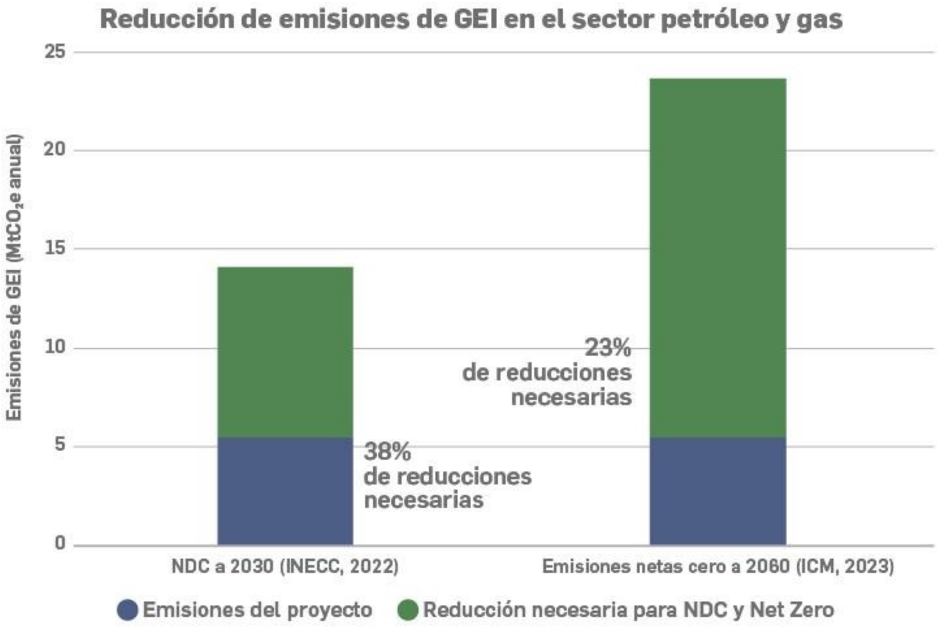


Although the project is within the limit of natural gas production and use to achieve zero emissions by 2050, its contribution is important and, if this natural gas can be replaced by renewable sources, it will be possible to achieve zero emissions by 2050.

could achieve the required GHG emission reductions more quickly. With this project it would be possible to install up to 37.7 GW of installed wind capacity or 54.4 GW of installed solar PV capacity. This represents 11% and 7% of the capacity required, respectively, to achieve the IEA net emissions scenario. Likewise, the amount of LNG delivered for use in Asia (822,800 MMscf), and the GHG emissions associated with its burning, are equivalent to the emissions from approximately 10.8 million light vehicles, and the carbon sequestered by 21.4 million hectares of forest in the United States (EPA, 2024).

Undoubtedly, the development of the project will have an impact on the country's mitigation commitments, mainly in terms of CH_4 emission reductions. With respect to the Nationally Determined Contributions (NDC), in order for the country to comply with a 35% reduction by 2030, 347 $MtCO_2e$ must be reduced by 2030. The annual GHG emissions in Mexican territory from this project are equivalent to 1.6% of this reduction. In the specific case of the oil and gas sector, the required reduction is 14 $MtCO_2e$, so the emissions generated by the project are equivalent to 38% of the required reductions in the NDCs (see Figure 6). In the case of 2050, the Government of Mexico has not established a trajectory needed to achieve net zero emissions, however, the Mexico Climate Initiative (ICM) estimated that 24 $MtCO_2e$ per year reduction is needed by 2060 in the domestic oil and gas sector in order to achieve this level of emissions in that sector. The project's annual emissions represent 22.5% of the required reductions in the oil and gas sector. It is important to note that this natural gas will be used in Asia, and Mexico will only serve as a platform for its transportation, so the economic contribution to the country is marginal.

Figure 6. Project emissions relative to the mitigation required for Mexico.



8. Conclusions

Life cycle is an important tool for quantifying environmental impacts along supply chain of products and services. In this work, emissions were estimated along the production and use of natural gas through its transportation by land and sea and its liquefaction. For this case study, production represented the most important component of the carbon footprint, mainly due to CH_4 emissions. Likewise, liquefaction and maritime transportation represent two other important sources of GHG emissions. Given the magnitude of the project and the actions required to achieve net zero emissions, the project becomes relevant and it will be necessary to find alternatives to stop the expansion of the use of fossil fuels or to promote the accelerated development of carbon-free sources.

9. Recommendations

Based on the results of this analysis, the following measures are recommended to improve the identification and control of GHG emission sources to achieve national and global climate change mitigation objectives.

- In order to quantify the real environmental impact of the project and make recommendations for measures to reduce or mitigate the climate impact of the project, it is necessary for the actors involved in the Saguaro Energía project to carry out a more detailed analysis of greenhouse gas emissions along the entire supply chain.
- As documented throughout this paper, there is a need for more detailed studies on the potential emissions generated in projects involving fossil fuels, and in particular other LNG export projects planned in Mexico. Also, these analyses need to be associated with the development of new techniques that improve the quantification of emissions in order to have more accurate estimates.
- While exercises are being carried out in the United States to improve this, in Mexico, it is necessary to have updated measurements and emission factors that reflect the conditions of the oil and gas infrastructure in the country.
- It is also necessary to assess in detail the environmental impact with a climate change approach of other similar projects, as well as their cumulative, synergistic and residual impacts, in addition to the social and economic impacts.

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11. Annexes

11.1. Life Cycle Assessment (LCA) Methodology

As part of the cycle analysis, the carbon footprint is a measure that quantifies the environmental impact. In this case, the amount of greenhouse gas (GHG) emissions generated by an activity or product throughout its cycle. To quantify the emissions of compound i (E_i), an emission factor (FEi) is used, as well as an activity data (DA). In this case, compound i corresponds to CO_2e and the activity data refers to the quantity that represents the activity or product. Emissions are estimated based on the following equation (CMM, 2016). It is important to note that total emissions E_i are presented in terms of a functional unit of product or service.

$$E_i = DA * FE_i$$

11.2. Results for vessels with 4-stroke and 2-stroke engines

The following table presents the emission factors considered for the estimation of CH_4 and CO_2 emissions for ships with 4-stroke and 2-stroke engines.

Emission factors for vessels with 4-stroke and 2-stroke engines.

Unburned methane emission factors	
Fraction of unburned methane 4-stroke (Balcombe, Heggo and Harrison, 2022)	**0.031**
Fraction of unburned methane 2-stroke (Balcombe, Heggo and Harrison, 2022)	**0.038**
Emission factors fuel combustion	
Steamship burnup (gCO_2/kgGNL) Raza and Schoyen, 2014; Bakkali and Ziomas, 2019).	**262.734**
Burn in 4-stroke vessels (gCO_2/kgGNL) 4-stroke (Raza and Schoyen, 2014; Bakkali and Ziomas, 2019).	**195.174**
Burn in 4-stroke vessels (gCO_2/kgGNL) Raza and Schoyen, 2014; Bakkali and Ziomas, 2019).	**162.144**
Fuel oil combustion (gCO_2/kgGNL)	**291.371**

Based on the emission factors used and the assumptions presented in the , the following figures present the gas balance.

Figure 7. Natural gas balance for the case of the 4-stroke engine vessel (Billions of standard cubic feet).

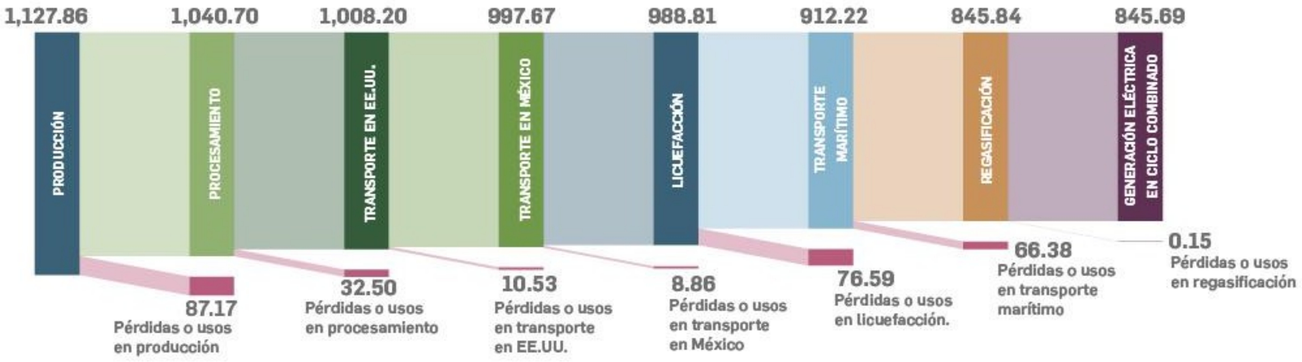
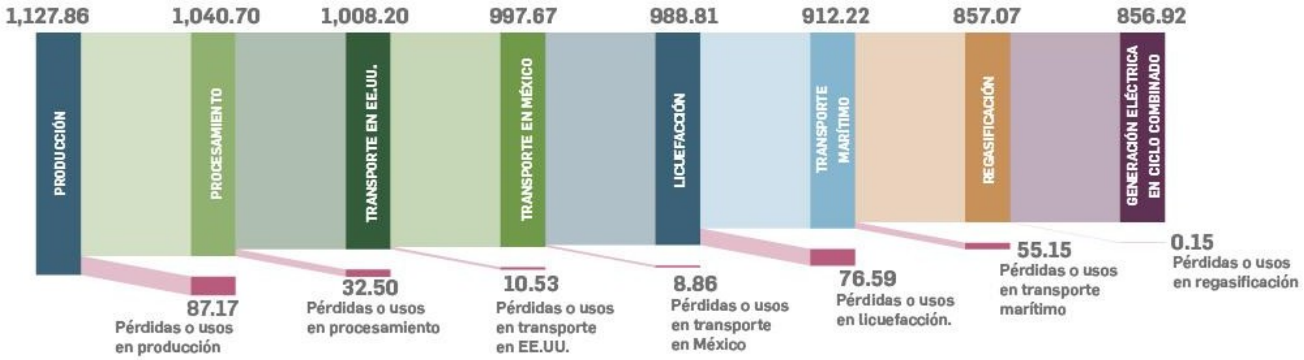


Figure 8. Natural gas balance for the 2-stroke engine vessel (Billions of standard cubic feet).



GHG emissions for the natural gas supply chain considering maritime transportation with 4-stroke and 2-stroke engine vessels are presented in the following table.

Table 12. GHG emissions for the supply chain (vessels with 4-stroke and 2-stroke engines).

Stage	Vessel (4 strokes)			Vessel (2 times)		
	CO_2 (tons per year)	CH_4 (tons per year)	CO_2e (PCG100) (tons per year)	CO_2 (tons per year)	CH_4 (tons per year)	CO_2e (PCG100) (tons per year)
Natural gas production and storage	2,507,710	224,465	9,196,767	2,507,710	224,465	9,196,767
Natural gas processing	2,042,902	25,918	2,815,252	2,042,902	25,918	2,815,252
Natural gas transportation in the United States	492,004	19,771	1,081,183	492,004	19,771	1,081,183

Natural gas transportation in Mexico	107,654	22,756.90	785,810	107,654	22,756.90	785,810
Liquefaction	4,542,024	1,974.79	4,600,873	4,542,024	1,974.79	4,600,873
Maritime transportation	3,503,888	40,458.45	4,709,549	2,910,922	41,201.36	4,138,723
Regasification combined cycle		2,996.32	89,290		3,036.12	90,476
Regasification gas turbine		2,996.32	89,290		3,036.12	90,476
Use for combined cycle	45,654,769	4.04	45,654,889	46,261,129	4.09	46,261,251
Use for gas turbine	45,654,769	4.04	45,654,889	46,261,129	4.09	46,261,251
Total (combined cycle)	**58,850,950**	**341,341**	**69,022,905**	**58,864,345**	**342,163**	**69,060,812**
Total (gas turbine)	**58,850,950**	**341,341**	**69,022,905**	**58,864,345**	**342,163**	**69,060,812**

Without taking account the use of natural gas in Asia, the supply chain GHG emissions for ships with 4-stroke and 2-stroke engines were 23.3 MtCO$_2$e and 22.7 MtCO$_2$e, respectively (Table 13). If their use in Asia is considered, total GHG emissions were 69.0 MtCO$_2$e for both cases. Emissions in the case of 2-stroke engine ships are marginally higher than in the 4-stroke case due to the fact that natural gas losses are lower and therefore there is a greater amount of natural gas to be burned. Emissions from the use of LNG represent approximately 67% for these cases. Likewise, the carbon footprint for the case of the 2-stroke engine vessel is lower due the fact that a larger amount of natural gas is delivered to the plant. LNG losses are lower in this case compared to the case of the 4-stroke engine vessel.

Table 13. Carbon footprint for the cases analyzed.

Stage	Footprint for the case of 4 times (tCO$_2$e per year/t of LNG delivered for use)	Footprint for the case of 2 times (tCO$_2$e per year/t LNG delivered for use)
Footprint per production (natural gas)	0.552583	0.545340
Footprint per processing	0.169153	0.166936
U.S. transportation footprint Mexican	0.064962	0.064111
transportation footprint	0.047215	0.046596
Liquefaction footprint	0.276441	0.272817
Footprint from maritime transport (natural gas)	0.282971	0.245413
Regasification footprint	0.005365	0.005365
Total footprint	**1.399**	**1.347**

As in the case of the steam-powered vessel, most of the carbon footprint of delivered natural gas corresponds to the natural gas production and processing stages in the United States, with 52% for the 4-stroke engine vessel and 53% for the 2-stroke engine vessel (Figure 9).

Figure 9. Carbon footprint distribution vessels with 4-stroke and 2-stroke engines.