UNIVERSIDAD DE INVESTIGACIÓN DE TECNOLOGÍA EXPERIMENTAL YACHAY

Escuela de Ciencias Químicas e Ingeniería

A techno-economic assessment of natural gas valorization in the Amazon region to increase the Liquefied Petroleum Gas (LPG) production in Ecuador

Trabajo de integración curricular presentado como requisito para la obtención del título de Petroquímico

Autor:
Ortiz Gutiérrez Darwin Patricio

Tutor:
Ricaurte Fernández Marvin José, PhD

Co-Tutor:
Viloria Vera Dario Alfredo, PhD

Urcuquí, octubre 2021

Urcuquí, 20 de diciembre de 2021

SECRETARÍA GENERAL
(Vicerrectorado Académico/Cancillería)
ESCUELA DE CIENCIAS QUÍMICAS E INGENIERÍA
CARRERA DE PETROQUÍMICA
ACTA DE DEFENSA No. UITEY-CHE-2021-00033-AD

A los 20 días del mes de diciembre de 2021, a las 11:30 horas, de manera virtual mediante videoconferencia, y ante el Tribunal Calificador, integrado por los docentes:

Presidente Tribunal de Defensa	Dr. DIAZ BARRIOS, ANTONIO , Ph.D.
Miembro No Tutor	Dr. SOMMER MARQUEZ, ALICIA ESTELA , Ph.D.
Tutor	Dr. RICAURTE FERNANDEZ, MARVIN JOSE , Ph.D.

El(la) señor(ita) estudiante **ORTIZ GUTIERREZ, DARWIN PATRICIO**, con cédula de identidad No. **1803975547**, de la **ESCUELA DE CIENCIAS QUÍMICAS E INGENIERÍA**, de la Carrera de **PETROQUÍMICA**, aprobada por el Consejo de Educación Superior (CES), mediante Resolución **RPC-SO-39-No.456-2014**, realiza a través de videoconferencia, la sustentación de su trabajo de titulación denominado: **A TECHNO-ECONOMIC ASSESSMENT OF NATURAL GAS VALORIZATION IN THE AMAZON REGION TO INCREASE THE LIQUEFIED PETROLEUM GAS (LPG) PRODUCTION IN ECUADOR.** , previa a la obtención del título de **PETROQUÍMICO/A**.

El citado trabajo de titulación, fue debidamente aprobado por el(los) docente(s):

Tutor	Dr. RICAURTE FERNANDEZ, MARVIN JOSE , Ph.D.
Co - Tutor	Dr. VILORIA VERA, DARIO ALFREDO , Ph.D.

Y recibió las observaciones de los otros miembros del Tribunal Calificador, las mismas que han sido incorporadas por el(la) estudiante.

Previamente cumplidos los requisitos legales y reglamentarios, el trabajo de titulación fue sustentado por el(la) estudiante y examinado por los miembros del Tribunal Calificador. Escuchada la sustentación del trabajo de titulación a través de videoconferencia, que integró la exposición de el(la) estudiante sobre el contenido de la misma y las preguntas formuladas por los miembros del Tribunal, se califica la sustentación del trabajo de titulación con las siguientes calificaciones:

Tipo	Docente	Calificación
Presidente Tribunal De Defensa	Dr. DIAZ BARRIOS, ANTONIO , Ph.D.	10,0
Miembro Tribunal De Defensa	Dr. SOMMER MARQUEZ, ALICIA ESTELA , Ph.D.	10,0
Tutor	Dr. RICAURTE FERNANDEZ, MARVIN JOSE , Ph.D.	10,0

Lo que da un promedio de: **10 (Diez punto Cero)**, sobre 10 (diez), equivalente a: **APROBADO**

Para constancia de lo actuado, firman los miembros del Tribunal Calificador, el/la estudiante y el/la secretario ad-hoc.

Certifico que *en cumplimiento del Decreto Ejecutivo 1017 de 16 de marzo de 2020, la defensa de trabajo de titulación (o examen de grado modalidad teórico práctica) se realizó vía virtual, por lo que las firmas de los miembros del Tribunal de Defensa de Grado, constan en forma digital.*

DARWIN PATRICIO ORTIZ GUTIERREZ
Firmado digitalmente por DARWIN PATRICIO ORTIZ GUTIERREZ
Fecha: 2022.01.04 10:20:53 -05'00'

ORTIZ GUTIERREZ, DARWIN PATRICIO
Estudiante

ANTONIO DIAZ BARRIOS
Firmado digitalmente por ANTONIO DIAZ BARRIOS
Fecha: 2022.01.04 10:01:04 -05'00'

Dr. DIAZ BARRIOS, ANTONIO , Ph.D.
Presidente Tribunal de Defensa

MARVIN JOSE RICAURTE FERNANDEZ
Firmado digitalmente por MARVIN JOSE RICAURTE FERNANDEZ
Fecha: 2021.12.22 09:47:08 -05'00'

Dr. RICAURTE FERNANDEZ, MARVIN JOSE , Ph.D.
Tutor

UNIVERSIDAD YACHAY TECH

Dr. SOMMER MARQUEZ, ALICIA ESTELA , Ph.D.
Miembro No Tutor

Firmado electrónicamente por:
ALICIA ESTELA SOMMER MARQUEZ

YEPEZ MERLO, MARIELA SOLEDAD
Secretario Ad-hoc

Firmado electrónicamente por:
MARIELA SOLEDAD YEPEZ MERLO

AUTORÍA

Yo, **DARWIN PATRICIO ORTIZ GUTIÉRREZ**, con cédula de identidad 1803975547, declaro que las ideas, juicios, valoraciones, interpretaciones, consultas bibliográficas, definiciones y conceptualizaciones expuestas en el presente trabajo; así cómo, los procedimientos y herramientas utilizadas en la investigación, son de absoluta responsabilidad de el/la autora (a) del trabajo de integración curricular. Así mismo, me acojo a los reglamentos internos de la Universidad de Investigación de Tecnología Experimental Yachay.

Urcuquí, octubre 2021.

DARWIN PATRICIO ORTIZ GUTIERREZ

Firmado digitalmente por DARWIN PATRICIO ORTIZ GUTIERREZ
Fecha: 2022.01.04 13:22:28 -05'00'

Darwin Patricio Ortiz Gutiérrez

CI: 1803975547

AUTORIZACIÓN DE PUBLICACIÓN

Yo, **DARWIN PATRICIO ORTIZ GUTIÉRREZ**, con cédula de identidad 1803975547, cedo a la Universidad de Tecnología Experimental Yachay, los derechos de publicación de la presente obra, sin que deba haber un reconocimiento económico por este concepto. Declaro además que el texto del presente trabajo de titulación no podrá ser cedido a ninguna empresa editorial para su publicación u otros fines, sin contar previamente con la autorización escrita de la Universidad.

Asimismo, autorizo a la Universidad que realice la digitalización y publicación de este trabajo de integración curricular en el repositorio virtual, de conformidad a lo dispuesto en el Art. 144 de la Ley Orgánica de Educación Superior

Urcuquí, octubre 2021.

DARWIN PATRICIO ORTIZ GUTIERREZ

Firmado digitalmente por DARWIN PATRICIO ORTIZ GUTIERREZ
Fecha: 2022.01.04 13:22:46 -05'00'

Darwin Patricio Ortiz Gutiérrez

CI: 1803975547

DEDICATION

"To my parents, Wilson and Esthela,

for helping me grow in life."

Darwin Patricio Ortiz Gutiérrez

ACKNOWLEDGEMENTS

I want to thank my Alma Mater, Yachay Tech University, for providing me with a high-quality education and giving me the necessary tools for my professional life.

I would like to express my appreciation and gratitude to my thesis advisor, Professor Marvin Ricaurte, and thesis co-advisor, Professor Alfredo Viloria, for supporting my work and academic formation.

Darwin Patricio Ortiz Gutiérrez

RESUMEN

La demanda de energía está creciendo mundialmente y diferentes fuentes de energía deben ser analizadas para asegurar un suministro apropiado. Una de las principales fuentes de energía es el gas natural, que es un combustible fósil ampliamente usado para proveer de energía y como insumo de la industria petroquímica. El gas licuado de petróleo (GLP) es una mezcla de hidrocarburos (propano y butanos) usado como un gas combustible, el cual es obtenido a través del procesamiento del gas y petróleo. La producción ecuatoriana de GLP (1.91 MMbbl/año) proviene principalmente de la refinería *Esmeraldas* y de la planta de gas *Shushufindi*, esta última ubicada en la región amazónica. Sin embargo, con esta producción no se puede abastecer la demanda del mercado ecuatoriano, y más del 80 % de este derivado es importado para satisfacer el mercado nacional. Al mismo tiempo, en la región amazónica, el gas natural producido no es completamente valorizado, y cantidades importantes de gas asociado son quemadas (~100 MMscfd), representando energía desaprovechada con un impacto ambiental significativo. Por esta razón, el presente trabajo busca desarrollar un análisis técnico y económico de la potencial valorización del gas natural en la región amazónica para incrementar la producción de GLP en el país. El estudio inició con una revisión detallada de la producción del gas asociado en la región amazónica. La información fue analizada considerando la ubicación geográfica de los campos, composición del gas, y condiciones operacionales. Luego, se realizó una visualización de la cadena de valor del gas natural. Seguidamente, se desarrolló un análisis técnico para procesar la corriente de gas asociado más atractiva de la región. Finalmente, se elaboró un análisis de factibilidad económica (clase V), considerando un análisis preliminar del gasto de capital (CAPEX) y un balance económico. Los resultados indican que procesando 14.6 MMscfd del campo Sacha, la producción de GLP en el Ecuador puede incrementarse en un 30 %. Una cantidad que representa 14.5 MMUSD/año en importación de este derivado a la economía ecuatoriana. La infraestructura requerida consiste en procesos convencionales (usando tecnología madura) de procesamiento de gas. El CAPEX estimado para la planta de gas, considerando condiciones locales, es de 21.9 MMUSD. Además, otros campos presentan características comerciales que deben ser analizadas para oportunidades de valorización industrial.

Palabras claves: gas natural, gas asociado, gas licuado de petróleo, región amazónica, Ecuador

ABSTRACT

The energy demand is growing worldwide, and different energy sources need to be analyzed to ensure the current supply. One of these sources is natural gas, a fossil fuel that is widely used to provide energy and as a feedstock of the petrochemistry industry. Liquefied petroleum gas (LPG) is a C_3/C_4´s hydrocarbon mixture used as fuel gas, obtained through natural gas and oil processing. The Ecuadorian LPG production (1.91 MMbbl/year) came mainly from the *Esmeraldas* refinery and *Shushufindi* gas plant. The last one is located in the Amazon region. However, this LPG production cannot meet the Ecuadorian market demand, and over 80 % of this commodity is imported to satisfy the national market. At the same time, in the Amazon region, the natural gas produced is not fully valorized, and an important quantity of the associated gas is flared (~100 MMscfd), representing energy wasted with a significant environmental impact. Therefore, this work aims to develop a technical and economic assessment of the potential natural gas valorization in the Amazon region to increase de LPG production in the country. The study started from a detailed review of the associated gas produced in the Amazon region. The data was analyzed considering the geographic location of the fields, gas composition, and operational conditions. Then, a visualization of the natural gas value chain was developed. Subsequently, a technical analysis was performed to process the stream of one of the most attractive gases in this region. Finally, an economic feasibility (class V) study was carried out, considering a preliminary analysis of the capital expenditure (CAPEX), and economic balance. The outcome of this study indicates that by processing 14.6 MMscfd of the associated gas from the Sacha field in the Amazon region, the national LPG production can increase by 30 %. An amount that represents 14.5 MMUSD/year in commodity imports to the Ecuadorian economy. The required infrastructure consists of conventional processes (using mature technologies) for natural gas processing. The estimated CAPEX for the natural gas processing plant is 21.9 MMUSD, considering local conditions. In addition, other fields also present high commercial characteristics to be analyzed for industrial valorization opportunities.

Keywords: natural gas, associated gas, liquefied petroleum gas, Amazon region, Ecuador

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

AU Gas	Associated Gas from Auca field
CAPEX	Capital Expenditure
BCF	Billion cubic feet (10^9 cubic feet)
BTEX	Benzene, toluene, ethylbenzene, and xylene
C_1	Methane
C_2	Ethane
C_3	Propane
C_4’s	Butanes (n-butane and i-butane)
C_5^+	Natural gasoline
CO_2	Carbon dioxide
Cyl	Cylinder
Cyl-15kg	15 kg cylinder
CU Gas	Associated Gas from Cuyabeno field
DEA	Diethanolamine
DEG	Diethylene glycol
DGA	Diglylamine
DIPA	Diisopropanolamine
EG	Ethylene glycol
EY Gas	Associated Gas from Edén Yuturi field
Gal	Gallons
gpm	Gallons per minute
GPM	Liquid hydrocarbon content expressed in gallons that can be obtained for every 1,000 cubic feet of natural gas at standard conditions
GHG	Greenhouse gas
GPSA	Gas Processors Suppliers Association
H_2S	Hydrogen sulfide
IN Gas	Associated Gas from Indillana field
ITT Gas	Associated Gas from Tiputini field
LA Gas	Associated Gas from Lago Agrio field
LI Gas	Associated Gas from Libertador field
LPG	Liquefied Petroleum Gas

LNG	Liquefied Natural Gas
MDEA	Methyldiethyanolamine
MEA	Monoethanolamine
MMbbl	Million Barrels
MMbbl/year	Million Barrels per Year
MMBTU	Million British Thermal Unit
Mscf	Thousand Standard Cubic Feet
MMscf	Million Standard Cubic Feet
MMscfd	Million Standard Cubic Feet per Day
MMUSD	Million dollars
MMUSD/year	Million dollars per year
NG	Natural Gas
NGL	Natural Gas Liquids
N_2	Nitrogen
OGE&EE	Optimization of Power Generation and Energy Efficiency
OPEX	Operational Expenditure
OY Gas	Associated Gas from Oso Yuralpa field
PA Gas	Associated Gas from Palo Azul field
ppmv	Parts per million by volume
Q	Flowrate
ShGP	Shushufindi Gas Plant
TEA	Triethanolamine
TEG	Triethylene Glycol
Tm/d	Metric tons per day
TREG	Tetraethylene glycol
USD/MMBTU	Dollar USD per million British Thermal Unit
USD/Mscf	Dollar USD per thousand Standard Cubic Feet
USD/bbl	Dollar USD per barrel
SA Gas	Associated Gas from Sacha field
SH Gas	Associated Gas from Shushufindi field
lb/MMscf	Pound per Million Standard Cubic Feet
BTU/ft^3	British Thermal Unit per Cubic Feet

CHAPTER I

INTRODUCTION

Natural gas (NG) is one of the principal energy sources worldwide. It is also considered one of the cleanest, safest, and more useful sources of energy. Owing to the increase in energy demand and the constant new policies of a lower-carbon economy, NG is becoming a convenient fuel, especially for power generation [1]. For 2020, NG supplied approximately 24.7 % of the global primary energy, just after the principal sources oil and coal [2]. The processing of natural gas is easier and less complex than oil processing [3]. Besides, natural gas is essential for the petrochemistry industry as a staple. The processing of natural gas can produce fuel derivatives and primary feedstocks for the production of ethylene, propylene, manufacture of light olefins, and other petrochemistry products. [4].

Liquefied Petroleum Gas (LPG) is a hydrocarbon mixture primarily composed of propane and butanes, used as fuel gas. LPG came from natural gas processing or crude oil refining [5]. LPG is widely used for residential, commercial, and industrial applications. In Ecuador, the principal usage of LPG is for residential activities, constituting over 90 % of the total demand, while the remaining quantity is for industrial, agroindustry, and transport activities [6]. Therefore, LPG is a critical fuel for the proper development of different economic and residential sectors in the country.

In Ecuador, the production of LPG came predominantly from *Esmeraldas* refinery and *Shushufindi* gas plant, and lower amounts from *La Libertad* refinery. Refineries obtain the LPG as an oil refining product, while the gas plant obtains the LPG by processing the associated gas from the Amazon region [6,7]. The Ecuadorian LPG demand has increased in the last few years. For 2020, 14.33 million barrels (MMbbl) of LPG were necessary to meet the national market needs. However, the national LPG production, of approximately 1.91 million barrels per year (MMbbl/year), was insufficient, and over 80 % of this commodity was imported to satisfy the domestic demand, with a total expense of 358.72 million dollars (MMUSD) [6,8].

Worldwide, oil extraction yields associated gas, which in some instances is used to produce natural gas liquids, fuel for the turbines on-site, or well reinjection [9]. However, the largest source of gas flaring came from associated gas. Gas flaring is the burning of associated gas because of many issues such as market and economic limitations, lack of appropriate infrastructure and regulations, and even political will. This practice results in the release of different pollutants, including carbon dioxide, methane, and black carbon [10,11]. Thereby, gas flaring is identified as a source of greenhouse gas (GHG) emissions [12]. The World Bank estimates that in 2020 approximately 5,015 billion cubic feet (BCF) of natural gas were flared in the world [13]. As this practice is identified as a waste of valuable resources with a considerable environmental impact, all attempts should be made to maximize the energy efficiency and reduce flaring to the lowest amount and only for technical reasons and safety [12,14].

In the Ecuadorian Amazon region, associated gas is widely produced as a by-product of oil extraction. By 2020, the associated gas produced in this region was 36,206 million standard cubic feet (MMscf) [15]. The efforts to take advantage of associated gas and improve energy efficiency have attracted attention in recent years. However, approximately 100 million standard cubic feet per day (MMscfd) of associated gas are still flared in the Amazon region [16]. In terms of energy generation, each 1 MMscfd of associated gas flared represents approximately 10 MMUSD/year in diesel imports [17].

This work, therefore, focuses on natural gas valorization in the Ecuadorian Amazon region to take advantage of the associated gas produced to ensure and increase the national LPG production and reduce the import dependency on this commodity. In the same way, to reduce the amount of gas flaring and its related environmental impact along the Amazon region. Hence, the present work started from a review and analysis of the associated gas produced in the Amazon region. Then, a valorization of the associated gas was visualized. Subsequently, a technical analysis was performed to take advantage of natural gas, considering the available techniques for gas processing. Finally, an economic feasibility (class V) study was carried out, considering a preliminary analysis of the capital expenditure (CAPEX), and economic balance.

1.1. Problem Approach

In Ecuador, the domestic LPG demand has increased in the last few years because of the wide usage in residential, industrial, agro-industrial, and transport sectors. However, in 2020, the national LPG production only covers 13.33 % of the domestic demand, and over 80 % of this commodity was imported. These imports represent significant expenses to the Ecuadorian economy, an average of 358.72 MMUSD per year [6,8].

On the other hand, the processing of associated gas can produce valuable natural gas liquids (NGL) products, which can increase industrial revenue. One of the widely used NGL products that can be obtained by gas processing is the LPG [4,18]. However, the associated gas produced along the Amazon region is not fully used, and a considerable quantity of the associated gas is flared [16,19]. The last practice constitutes a waste of energy with a significant environmental impact [12,19]. Gas flaring has also negatively affected the wildlife and public health of local communities in the region [20–22].

Considering the increasing energy demand, low national LPG production, high LPG import dependency, and gas flaring and its related environmental and social impact, the associated gas valorization in the Amazon region can bring multiple energy, economic, and social benefits (Figure 1). Therefore, this work seeks to develop a technical and an economic assessment to valorize the natural gas produced in the Amazon region to increase the LPG production in Ecuador.

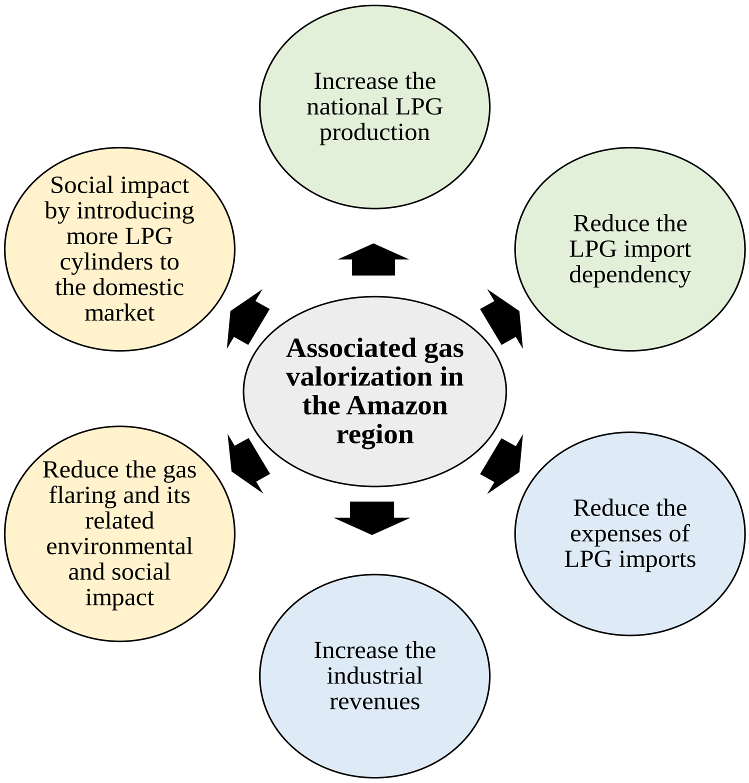

Figure 1. *Benefits of associated gas valorization in the Amazon region*

1.2. Objectives

1.2.1. General Objective

To develop a technical and an economic assessment of natural gas valorization in the Amazon region to increase the LPG production in Ecuador.

1.2.2. Specific Objectives

- To identify the current production, composition, and operational conditions of the associated gas generated in the different hydrocarbon fields in the Amazon region.
- To analyze the associated gas produced in the hydrocarbon fields along the Amazon region and the feasibility of industrializing them.
- To propose potential technology to process the associated gas produced in the Ecuadorian Amazon region as an alternative and potential use to produce LPG.
- To develop an economic feasibility analysis of the proposed technology for gas processing and its valorization.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1. Natural Gas

Natural gas is a mixture of gaseous hydrocarbons of low molecular weight, mainly composed of methane (C_1) and ethane (C_2), and usually propane (C_3), butanes (C_4´s), and a smaller amount of heavy hydrocarbons (C_4^+) and non-hydrocarbon components, such as nitrogen (N_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), oxygen (O_2) and sometimes valuable helium (He) [23]. NG usually is found underground at high-pressure conditions [24].

Natural gas comes from both conventional and unconventional sources. The conventional gas is usually inside multiple porous zones in occurring natural rocks such as carbonates, sandstones, and siltstones. Unconventional gas came from coal (coal-bed methane), tight sands, shales gas, geo-pressurized aquifers, and gas hydrates. Most of the time, gas from unconventional sources is more challenging to obtain owing to the required new technologies [24].

Conventional natural gas occurs in deep reservoirs, where it can be produced as associated or non-associated gas. Associated gas (also known as oil-well gas) is produced during the crude oil extraction and then separated at the casinghead or wellhead [18]. Crude oil production always yields associated gas, which emerges as the pressure decreases on the way to and on the surface. On the other hand, non-associated gas occurs in reservoirs that do not contain crude oil or just a few quantities of them. Typically, the majority of the non-associated gas composition contains methane. Non-associated gas is also known as “free gas” [9].

The associated and non-associated gas compositions vary depending on the field, formation, or reservoir form extracted [9]. The typical composition of these gases is shown in Table 1.

Table 1. *Typical natural gas compositions (mole %)*

	Canada (Alberta)	**Western Colorado**	**Miskar Field Tunisia**	**Rio Arriba County, New Mexico**	**Cliffside Field, Amarillo, Texas**
C_1	77.1	29.98	63.92	96.91	65.8
C_2	6.6	0.55	3.35	1.33	3.8
C_3	3.1	0.28	0.96	0.19	1.7
C_4´s	2.0	0.21	0.54	0.05	0.8
C_5´s	3.0	0.25	0.63	0.02	0.5
N_2	3.2	26.10	16.91	0.68	25.6
CO_2	1.7	42.66	13.59	0.82	0.0
H_2S	3.3	0.0	0.09	0.0	0.0
He	0.0	0.0	0.0	0.0	1.8

Source: Adapted from [25]

Associated gases usually are rich in natural gas liquids. It implies that these gases incorporate ethane, propane, butanes, and heavier molecular weight hydrocarbons [9]. Industry uses the term GPM to quantify the content of liquids in a gas mixture, which refers to the gallons of liquids recoverable per thousand standard cubic feet (Mscf) of gas. Calculation of the GPM requires data from the gas composition (mole basis) and gallons of liquid per lb-mole. The extraction of liquids from natural gas gives a higher economic value in sales than just natural gas [18].

According to its liquids content (proportion of heavy hydrocarbons), natural gas is listed as rich gas or lean gas. Rich gas is considered when the amount of liquids (C_2^+ or C_3^+) is potentially recoverable, usually when the GPM is 3 gal/Mscf or higher. On the other hand, gas is considered lean when the GPM is less than 3 gal/Mscf [18].

Simultaneously, natural gases are classified according to the content of acid gases, specifically hydrogen sulfide (H_2S). Sour gas is known when there are unacceptable quantities of H_2S, which can be odiferous and corrosive. On the contrary, sweet gas has a negligible amount of H_2S, generally less than 4 ppmv [18]. Other acid gases such as CO_2 can be allowed in many high levels, 3-4 mole % [26].

Natural gas and crude oil operations (exploration, drilling, and production) are developed in onshore and offshore facilities. In the industry, onshore refers to the operations in underground reservoirs on land. In contrast, offshore refers to the operations throughout a coastline or in open ocean waters in wells on the seabed [27,28]. Offshore operations are much more expensive than onshore operations because of their complex systems and technology required [29].

2.1.1 Natural Gas Processing

The processing of natural gas is an essential component in the gas industry. It depends on the feed gas compositions and obeys the requirements for the desired gas product and market specifications [4]. The principal aim of gas processing plants includes gas dehydration, acid gases removal, hydrocarbon liquids recovery, and fractionation [18]. The main products of this process include liquefied petroleum gas (LPG), natural gasoline (C_5^+), and residual gas. Figure 2 is a scheme of the typical stages of natural gas processing.

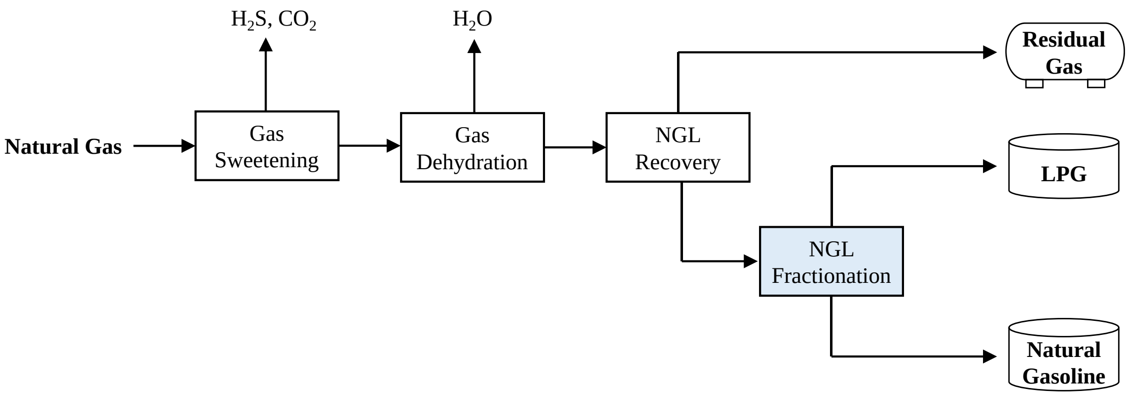

***Figure* 2.** *Scheme of natural gas processing*

- **Gas Sweetening:** In this process, the main purpose is to reduce the amounts of acid gases such as hydrogen sulfide (H_2S), carbon dioxide (CO_2), and other sulfur species (impurities) from the input stream. It is indispensable to meet the required specifications and avoid corrosion and plugging problems in the following stages of the process. The standard values to avoid the latter problems are H_2S < 4 ppmv and CO_2 < 2 vol.% [18,24]. However, if there is a cryogenic process in the following stages, it is needed more CO_2 remotion to avoid its freezing and meet the product specifications [24]. Commonly, the methods to remove acid gases are based on liquid-phase absorption processes, including chemical, physical, and hybrid solvents. In the chemical solvents processes, the absorption of acid gases is done principally by using amines in water solutions (10 to 65 wt % amines). Amines typically used are monoethanolamine (MEA), diethanolamine (DEA), triethanolamine (TEA), diglycolamine (DGA), methyldiethyanolamine (MDEA), and diisopropanolamine (DIPA). Figure 3 shows a simplified flow sheet of a common gas sweetening process by chemical reaction [30].

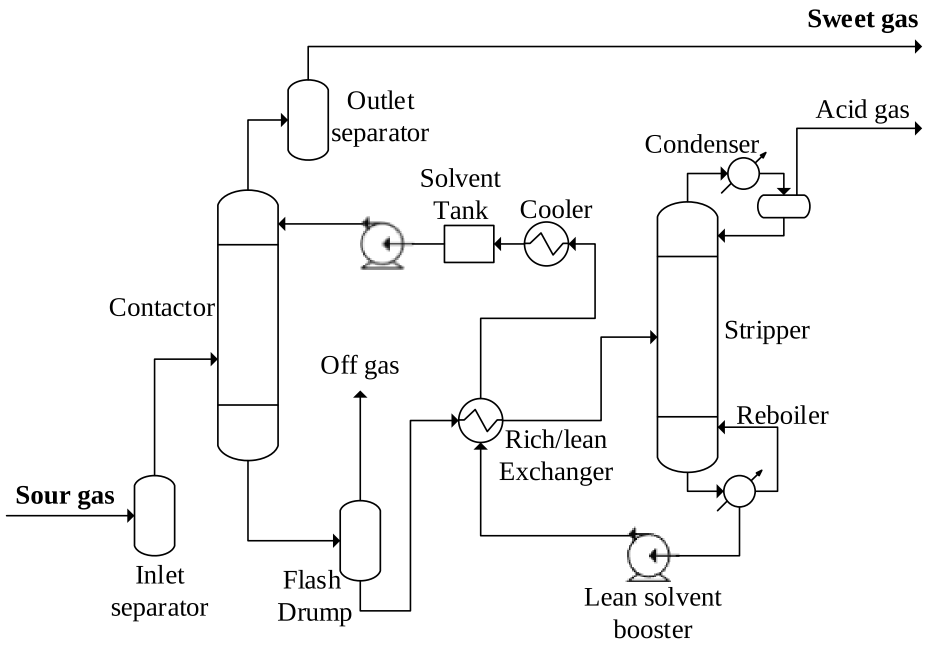

Figure 3. *Schematic of typical gas sweetening process by chemical reaction*

In the physical solvent processes, the gas removal is done by only physical absorption, without chemical reactions. In contrast, hybrid solvent processes handle a mixture of physical and chemical solvents [18,30].

- **Gas Dehydration:** Since the gas stream came from wells and a previous amine treatment, this stream is water-saturated. In the gas dehydration step, water is removed from the stream to decrease corrosion and prevent gas hydrate formation. The water content specifications in natural gas usually range from 4 to 7 lb/MMscf [18]. However, the specification to prevent hydrate formation in cryogenic processes is $[H_2O] \leq 0.1$ ppmv or even less. The conventional methods of water remotion are physical absorption and adsorption. In physical absorption, the gas is contacted with a liquid solvent that absorbs the water vapor. The most usual absorbent (solvent) is triethylene glycol (TEG), but there are others such as ethylene glycol (EG), diethylene glycol (DEG), and tetraethylene glycol (TREG) [18]. Figure 4 illustrates a simplified flow sheet of the glycol dehydration process.

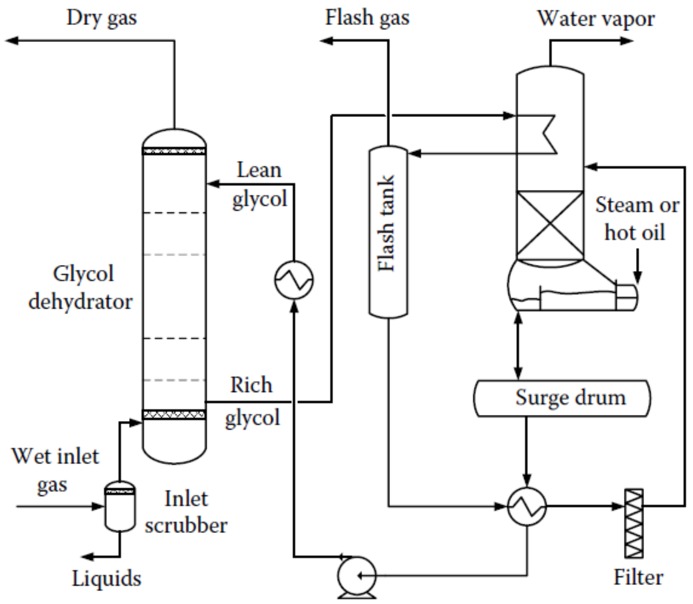

Figure 4. *Schematic of typical glycol dehydration process* [18]

In physical adsorption, a solid is used as the adsorbent medium, the usual adsorbent is a molecular sieve, and sometimes silica gel and activated alumina because of their high surface-to-volume ratio [18].

- **Natural Gas Liquids Recovery**: In this stage, the principal aim is to separate the natural gas liquids such as ethane, propane, and heavy hydrocarbons from the gas stream, in order to meet the pipeline heating specifications and create valuable NGL hydrocarbon products [4,18]. The recovery process uses low-temperature separation to condense the NGL. The technology used depends on desired products, processed volume, inlet composition, and inlet pressure [18]. Thereby, the most common refrigeration methods include Joule-Thompson valve expansion, mechanical refrigeration, and turboexpanders.

Joule-Thompson valve expansion (J-T valve): This system employs the Joule-Thompson effect to decrease the gas temperature by an isenthalpic expansion. The consequence of this temperature reduction is liquid (hydrocarbons and water) condensation. A J-T valve expansion system is applied for cases where enough pressure is available (high or supercritical pressures) to meet the desired product and separation [24,30]. A J-T system has several advantages over the other methods, such as simple design and operation, low cost, no rotating equipment, low maintenance, and extensible use to different flowrates and compositions [24].

Mechanical refrigeration: when enough pressure is not available, mechanical refrigeration is used to extract heavy hydrocarbon components [30]. In this system, NGL are condensed using a refrigerant that chills the feed gas into the low-temperature separation. The most usual refrigerant is propane, but there are also other commercial refrigerants such as ammonia [4]. Propane can supply coolant at -40 ºF at atmospheric pressure [24]. Figure 5 illustrates a simplified flow sheet of NGL recovery with a mechanical refrigeration system [30].

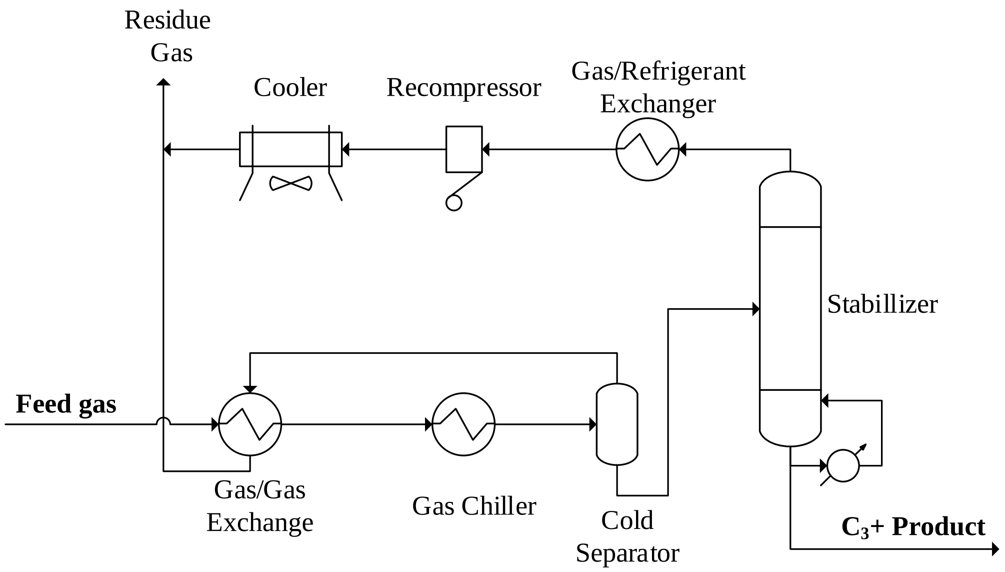

Figure 5. *NGL recovery with mechanical refrigeration process (straight refrigeration)*

Turboexpander: In this system, the feed gas pressure is used to produce the required refrigeration by an expansion through the turboexpander. The turboexpander recovers the useful work from this gas expansion and condenses the NGL. Since the expansion is near isentropic, the turboexpander significantly achieves lower temperatures than those for the J-T valve [30]. Therefore, this technology is the most used in cryogenic NGL recovery processes (deep NGL extraction), with minimum temperatures below -150 ºF achieved, i.e., for ethane recovery or often for high propane recovery [4]. However, turboexpanders require considerable operation attention and maintenance, which implies more operation costs than the other technologies [24].

- **Natural Gas Liquids Fractionation**: The NGL produced in the last stage are processed into individual products by fractionation. It implies the separation of components because of the relative volatility (boiling points) through a series of distillation columns (fractionation towers). Because of different NGL compositions and product specifications, there are some options for fractionation train design [24]. Usually, NGL products from a fractional process include demethanized product (C_2^+), deethanized product (C_3^+), propane/butane mixture (LPG), butanes (C_4´s), natural gasoline (C_5^+), and others [30]. Figure 6 shows a typical NGL fractionation train that recovers hydrocarbon liquids [24].

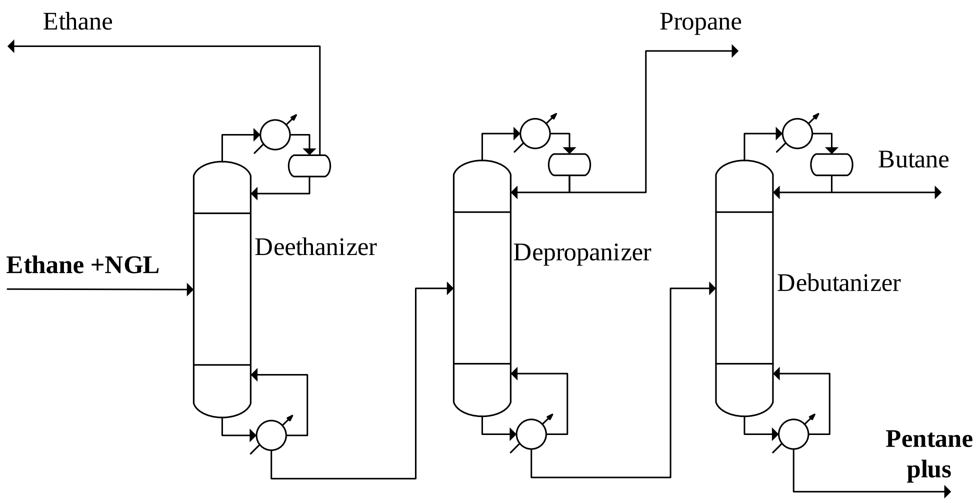

Figure 6. *Typical NGL fractionation train*

2.2. Natural Gas Liquids Products

Natural gas liquids extraction can increase the revenue from the processed gas stream by selling these NGL in higher-priced markets than natural gas markets. In places where demand and infrastructures of NGL exist, their extraction is leasable [4]. Table 2 shows the different NGL products and their potential markets. The widely used NGL products that can be obtained by natural gas processing have a considerable market application.

Table 2. *NGL products and markets*

NGL products	Market Use
Ethane (C_2)	Petrochemical feedstock for manufacturing ethylene.
Propane (C_3)	Fuel use as a component in LPG.
	Petrochemical feedstock for manufacturing propylene and ethylene.
	Residential and commercial fuel in rural areas, transportation fuel, and cooking grills.
Isobutane (i-C_4)	Refinery feedstock to alkylation unit, methyl-tertiary-butyl-ether feedstock.
	Fuel use as a component in LPG.
Normal butane (n-C_4)	Gasoline blending, petrochemical feedstock for the manufacture of light olefins.
	Fuel use as a component in LPG, isomerized to *i*-butane.
Natural Gasoline (C_5^+) *	Refinery feedstock to reformer or isomerization unit.
	Petrochemical feedstock for the manufacture of light olefins.

*Natural gasoline is a North America term, also referred to as light naphtha or condensate in other regions

Source: Adapted from [4]

Worldwide, gas plants process both associated and non-associated gas to produce high-quality natural gas and hydrocarbon liquids. The sale of these liquids provides significant incomes and optimizes the profits in the industry [18].

2.2.1. Liquefied Petroleum Gas

One of the natural gas processing products is liquefied petroleum gas, a hydrocarbon mixture primarily comprised of propane and butanes (C_3 and C_4´s), and a low amount of other hydrocarbons. The LPG composition can vary widely because of regional norms and climate specifications. Liquefied petroleum gas exists in the gaseous state at atmospheric conditions (60 ºF and 14.69 psia). However, it can be turned into a liquid state under moderate pressure at ambient temperature [5].

Most of the LPG comes from natural gas processing, and the remainder is a by-product derived from crude oil refining [31]. Naturally, LPG processed is odorless, colorless, and heavier than air. However, for commercial purposes, a mercaptan (odorizing agent) is added into the raw LPG for safety measurements [32]. To conserve space LPG is pressurized in steel vessels (cylinders or bulk containers) at ambient temperature. In the same way, LPG can be refrigerated for transport and later stored as a liquid [33].

In the market, according to volatility, LPG is classified as commercial propane (high volatility), commercial butane (low volatility), and commercial propane-butane mixture (intermediate volatility) [34]. Commercial propane is a hydrocarbon mixture that predominantly contains propane and/or propylene. Commercial butane is a hydrocarbon mixture that predominantly contains butanes and/or butylenes [30]. Table 3 shows an acceptable range of the significant components of LPG in different regions.

Table 3. *LPG composition in different regions*

Region	Fuel Compositions % (vol/vol)			Source
	Propane	Propylene	Butane	
Canada	92.5-100	0-5	0-2.5	[31]
United States	92.5-100	0-5	0-2.5	[31]
Mexico	60		40	[31]
Ecuador	60-100		0-40	[35]

LPG has a considerable heating value (~1,400.91 BTU/ft^3), which is much higher than the average heat value of natural gas. Hence, LPG is widely used as a fuel gas for residential, commercial, and industrial applications. Besides, it is used as an alternative for automotive fuel and as a feedstock in petrochemical uses [1].

2.2.2. LPG recovery process

LPG production is achieved using fractionation columns, which arrangement comprises deethanizer, depropanizer, debutanizer, and butane splitter units. In the deethanizer unit, the ethane plus stream (raw NGL) is separated into ethane and propane plus (propane and heavier components). In the depropanizer unit, the propane is separated from the butane and heavier components. In the debutanizer unit, the butanes are separated, and these butanes are further separated in the butane splitter unit [30]. A schematic diagram of the fractionation process for the LPG recovery is shown in Figure 7 [25].

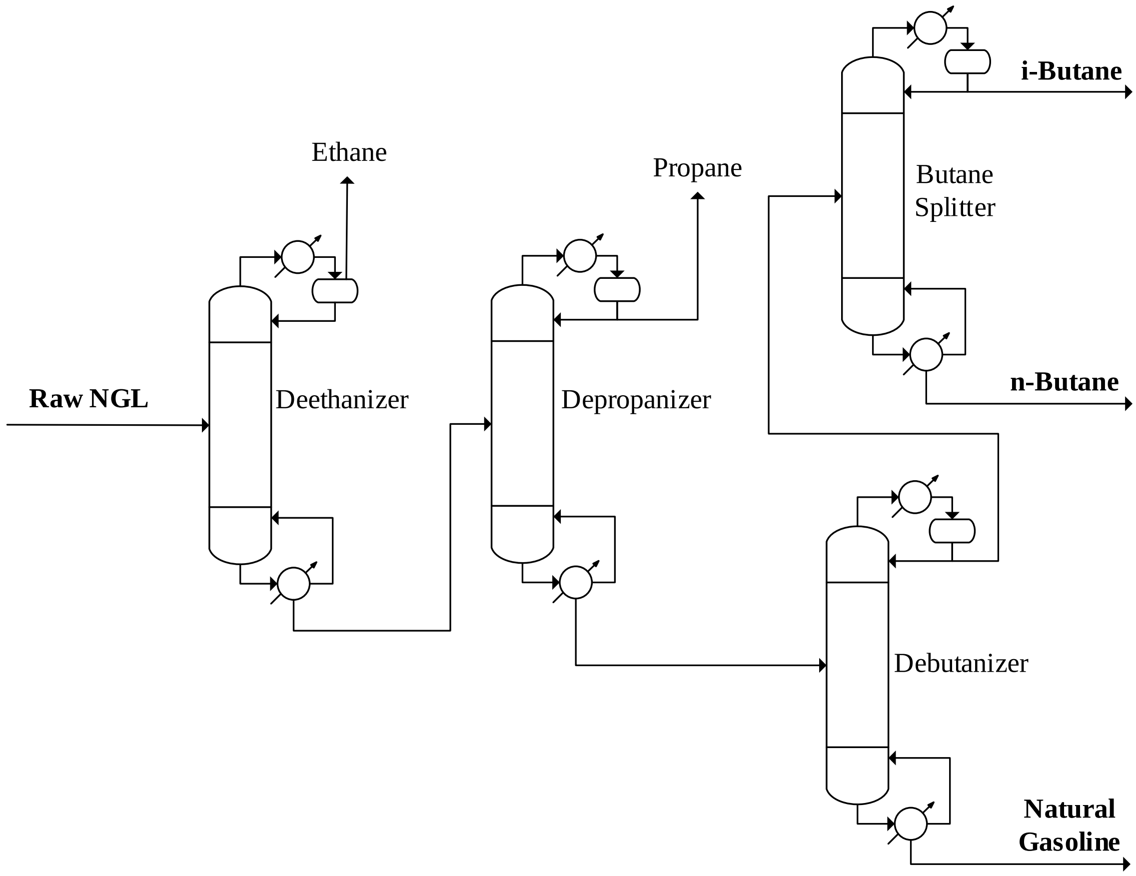

Figure 7. *Fractionation System for LPG recovery*

As seen in this chapter, natural gas is processed through different stages to produce the desired natural gas liquids in the industry. In this way, the next chapter will review natural gas and the current processed products in the Ecuadorian industry.

CHAPTER III

NATURAL GAS INDUSTRY IN ECUADOR: A BRIEF REVIEW

The hydrocarbon resources in Ecuador are mainly spread out in the Oriente Basin (Amazon region) and less in the Tumbes Basin (southwest of the country) (Figure 8) [19]. These resources are divided into various blocks, which are geographic area divisions containing oil and gas fields with different wells where the oil and gas production is carried out. In Ecuador, natural gas production comes from free natural gas extraction as non-associated gas and from oil extraction as associated gas.

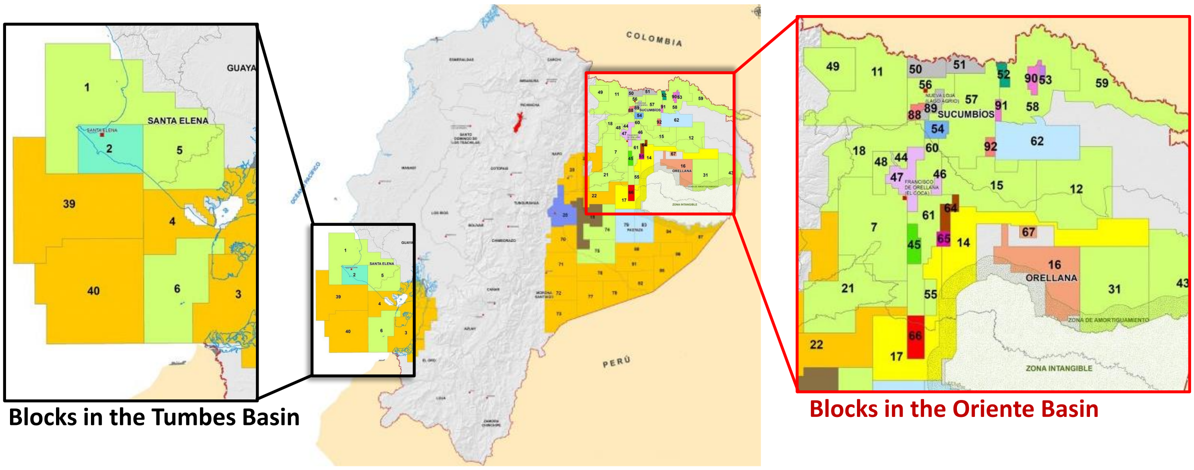

Figure 8. *Hydrocarbon resources in Ecuador*

Non-associated gas is produced in the Amistad field (block 6), an offshore facility located in the Gulf of Guayaquil in southwestern Ecuador. The gas produced in this field for 2020 was 9,465 MMscf which implies around 26 MMscf per day [15]. First, the water content in the natural gas is reduced in a dehydration plant located in Bajo Alto (El Oro province). And then, the natural gas is delivered mainly to the *Termogas Machala* power plant and the remainder to the *Bajo Alto* liquefaction plant, both located in Oro province too. *Termogas Machala* plant uses the natural gas for national electricity generation. *Bajo Alto* plant processes the natural gas into liquefied natural gas (LNG) to sell it mainly to the ceramic industry and a small quantity to other industries and residential sectors in the national market [36–38]. Figure 9 shows the offshore Amistad facilities.

Figure 9. *Amistad offshore facilities* [36]

Associated gas is widely generated along the Amazon region, directly related to crude oil extraction. In this region, the associated gas production reported for 2020 was 36,206 MMscf [15]. In recent years, the efforts to take advantage of this gas and improve energy efficiency have drawn attention by using this resource for electricity generation (within a few fields) and the production of derived products. However, over 100 MMscf of associated gas still are flared per day [16]. There is still a considerable amount of gas flaring in the region, which is considered a waste resource and a cause of environmental pollution (Figure 10) [19]. Since gas flaring has negatively affected the health of the local inhabitants of the region, there have been legal drawbacks between the local communities and the hydrocarbon companies. The communities seek that companies aim to reduce gas flaring and change the present gas release technology, which wastes considerable energy [22].

Figure 10. *One of the different flare sites (at Auca field) in the Amazon region* [20]

3.1. Liquefied Petroleum Gas Market

In Ecuador, liquefied petroleum gas is crucial for the proper development of different economic and residential sectors. In 2020 the domestic demand of this commodity was approximately 14.33 MMbbl (Figure 11), 90.87 % of the LPG was used for residential activities, 6.78 % for industrial activities, 1.75 % for agroindustry activities, while the remainder was used for transport activities [6]. LPG is packaged into steel vessels (cylinders) with a nominal capacity of 5, 10, 15, and 45 kg for market purposes [39]. For residential uses, LPG is mainly distributed in 15 kg cylinders. For industrial uses, LPG is mainly distributed in 45 kg cylinders and bulk containers, whereas for agro-industrial uses, it is commercialized in bulk containers [40].

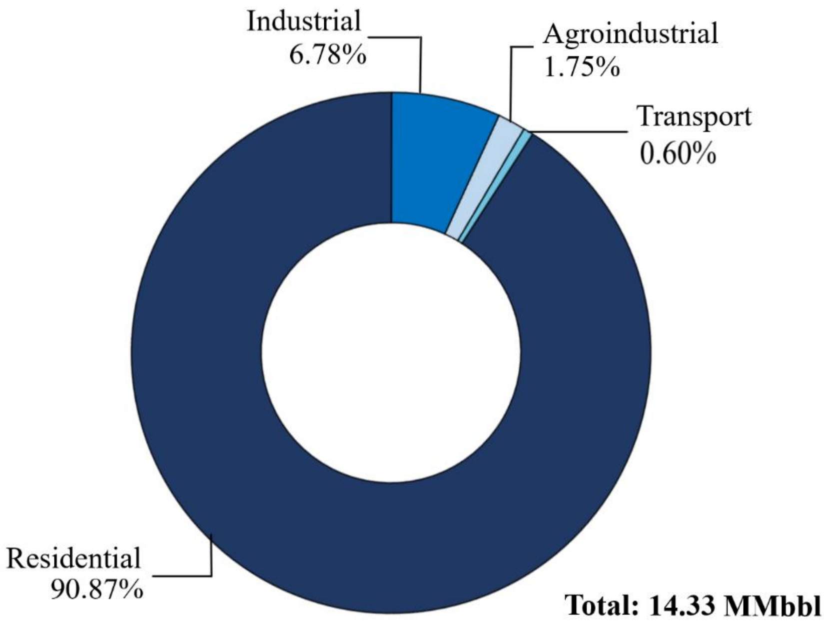

Figure 11. *LPG demand in Ecuador by sectors in 2020*

The Ecuadorian LPG production came from different facilities such as *Esmeraldas* and *La Libertad* refineries and the *Shushufindi* gas plant. Refineries obtain the LPG as an oil processing product, while the gas plant obtains the LPG by processing the associated gas from the Amazon region [7]. The national LPG production for 2020 was approximately 1.91 MMbbl. The principal production came from *Esmeraldas* refinery with almost 51.75 % and *Shushufindi* gas plant with almost 47.98 % of the LPG [6]. Although this commodity is fundamental in the Ecuadorian energy supply, the national LPG production cannot meet the domestic market needs. The LPG production and demand in recent years in Ecuador reported by the Ecuadorian

Ministry of Energy and non-Renewable Resources [38] and Petroecuador [6] are shown in Figure 12.

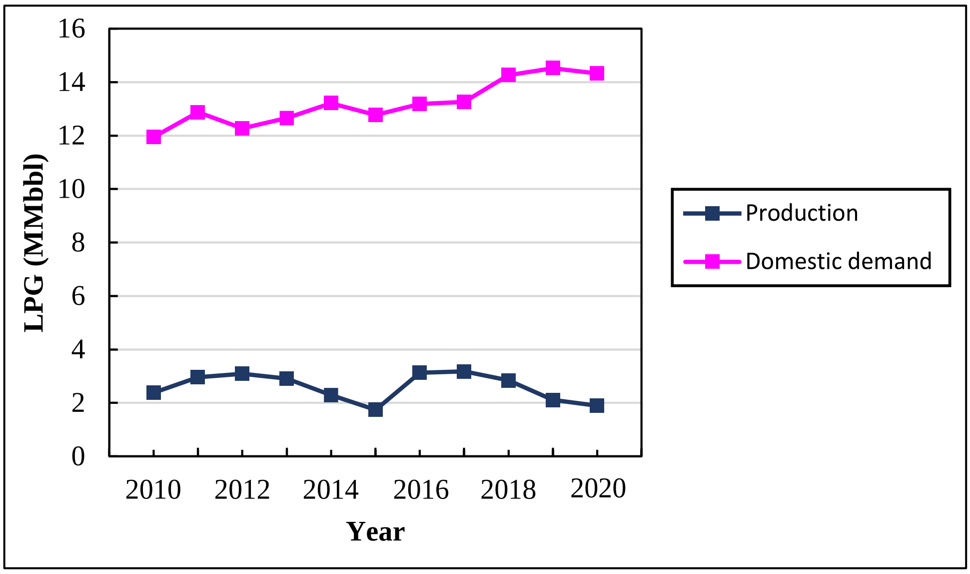

Figure 12. *LPG production and demand in Ecuador in recent years*

As noted above, the domestic LPG demand has increased in the last few years. However, the single national LPG production cannot satisfy the domestic demand and, therefore, it is crucial LPG imports. For instance, in 2020, approximately 12.42 MMbbl of this commodity was imported, representing around 86.67 % of the domestic demand (Figure 13). In economic terms, 358.72 MMUSD was spent to cover the imports in this year [6,8]. These economic expenses have been similar in the last years, even though the *Shushufindi* Gas Plant produces LPG from the raw associated gas in the Amazon region.

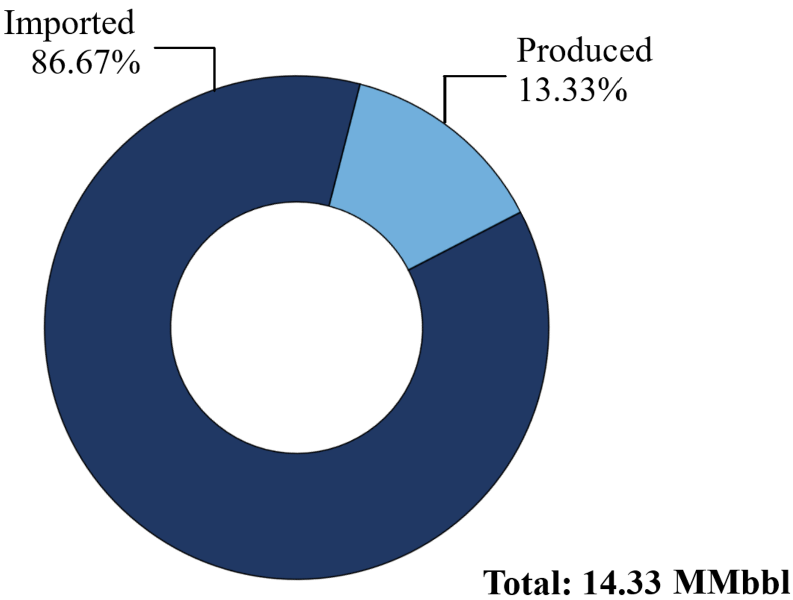

Figure 13. *LPG supply in Ecuador in 2020*

3.2. Shushufindi Gas Plant

The *Shushufindi* gas plant (ShGP) is part of the Shushufindi industrial complex, located in the Shushufindi canton (Sucumbios province) in the Amazon region. The gas plant was designed to use associated gas from the oil fields to produce liquefied petroleum gas and natural gasoline [41]. The feed streams came into this plant as gas and condensate streams. The gas stream came from Central, South, and North Shushufindi gas capture stations, and the condensates came from Central, South, and North Secoya gas capture stations [35]. The LPG products are delivered by pipelines to Quito and sold in the different national markets [42]. For 2019, the ShGP processed 14.14 MMscfd of associated gas and 78.83 gpm of condensates to produce 249.73 Tm/d of LPG [35,43]. The main parts of this gas processing plant are the reception and conditioning, the cooling, and the fractionation section [35]. Figure 14 shows a block diagram of the different process stages in the *Shushufindi* gas plant.

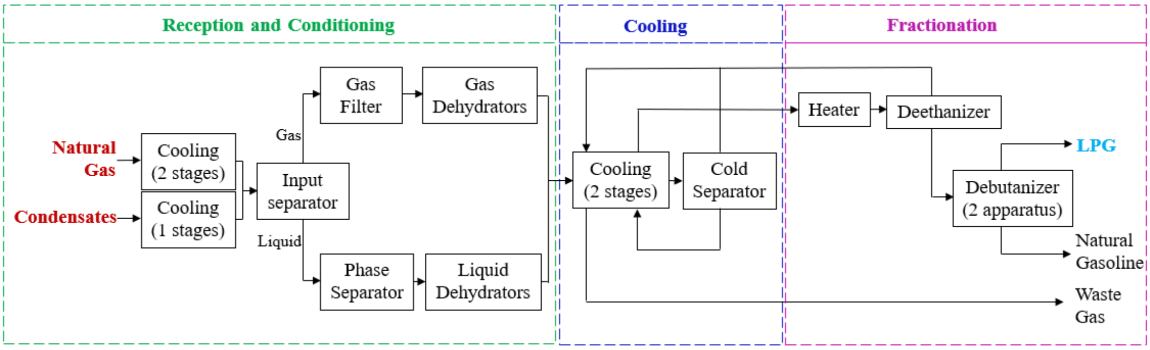

Figure 14. *Shushufindi Gas Plant block diagram*

Source: *Adapted from* [35]

Echeverria [35] studied the possibility of increasing the LPG production in the *Shushufindi* gas plant by operational improvements, but it requires investments, and the plant LPG production could increase by 30 %. In this way, it is important to develop more projects to help increase the current LPG production in the country. Therefore, there is a potential opportunity to valorize the associated gas from the Amazon region and produce more LPG.

CHAPTER IV

METHODOLOGY

To make a techno-economic assessment considering the natural gas valorization in the Amazon region to increase the LPG production in the Ecuadorian market is required to follow several steps summarized in Figure 15. The study started from a review of the associated gas produced in the Amazon region. The data was analyzed considering the field locations, gas compositions, and operational conditions. Then, a potential valorization of the associated gas was visualized. Subsequently, a technical analysis was performed to process one of the most attractive gases in this region, considering the conventional and available techniques. The natural gas processing stages included: sweetening, dehydration, natural gas liquid recovery, and fractionation. Finally, an economic feasibility (class V) study was carried out, considering a preliminary analysis of the capital expenditure (CAPEX), and economic balance. The LPG plant proposal was developed, considering all the aspects reviewed.

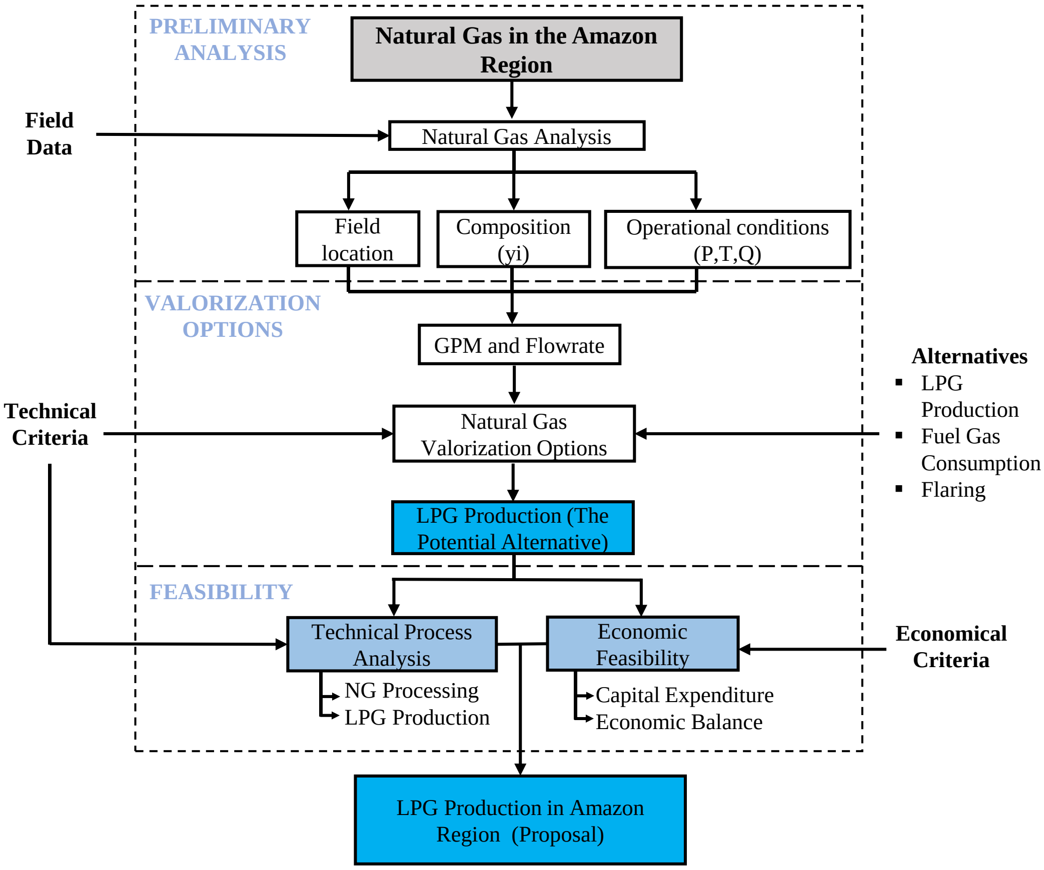

Figure 15. *Methodology diagram*

The bibliography research about the natural gas production data in the Amazon region was challenging in this study because of the lack of published information about the topic. The first step was to look for factual information about the fields which produce associated gas as a by-product of their hydrocarbon operations. The materials used in this work were compiled from different sources, including high-quality reports, degree-thesis, articles, standards, and other contributions in recent years published by several institutions such as the Ecuadorian Ministry of Energy and non-Renewable Resources (MERNNR), EP Petroecuador, Petroamazonas EP, the Ecuadorian Standardization Service (INEN), the U.S. Energy Information Administration (EIA), and the World Bank.

4.1. Natural Gas Analysis in the Amazon Region

The principal factors to consider for a commercial appreciation of the associated gas are the field locations, gas flowrates, and gas compositions. Once these parameters have been determined, it is viable to make an appropriate valorization of this resource.

4.1.1. Field Locations

The hydrocarbon fields in the Amazon region are arranged into different assets used to report information. These assets are considered a technical unit that manages one or more fields (which include platforms, production islands, wells, and facilities) focused on hydrocarbon exploration and extraction [44,45]. The assets selected for this work were those with associated gas production more significant than 1 MMscfd. Hence, the assets which meet this condition are listed in Figure 16.

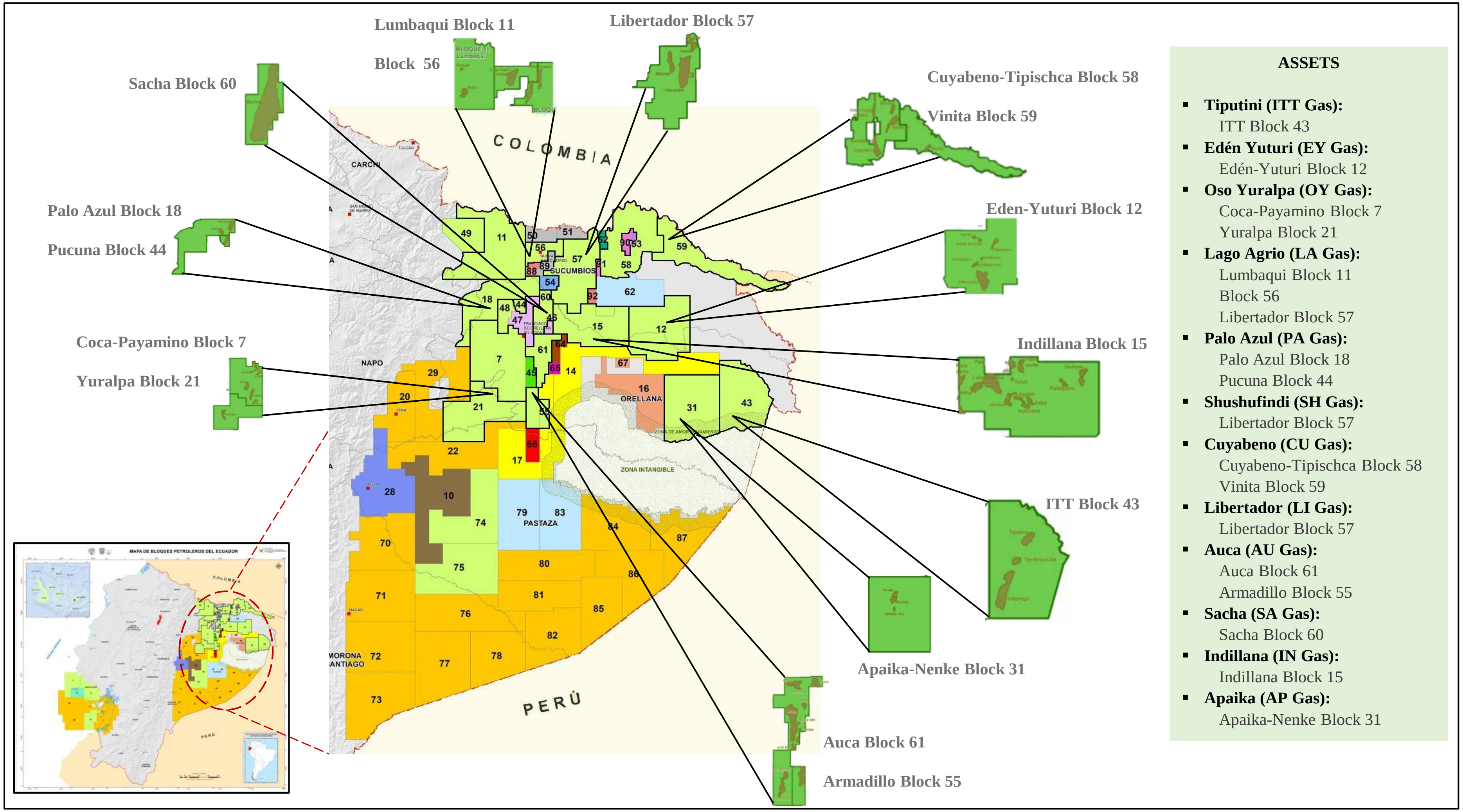

Figure 16. *Associated gas production in the Amazon Region*

Source: *Adapted from* [46,47]

4.1.2. Associated Gas Compositions

The data collected about the associated gas compositions were normalized to get an accurate analysis. Besides, note that, under consideration of this document, the gas composition data from a single field will represent the whole asset to obtain a generalized analysis. Therefore, when referring to a hydrocarbon field in this work, it refers to all the fields in the asset.

4.1.3. Flowrate and GPM

The gas flowrate of each field was calculated by an average of the last two months of production (April 15th to June 15th of 2021). This information is summarized in Table A.1 (Appendix A). Besides, the C_2^+ and C_3^+ GPM were calculated using each gas stream's flowrate and compositions (mole basis), following the theoretical Eq.1:

$$GPM = \frac{gallons\ of\ liquids\ recoverable}{thousand\ standard\ cubic\ feet\ of\ gas} = \frac{gal\ \ NGLs}{Mscf\ gas} \qquad (1)$$

The C_2^+ GPM considered the ethane, propane, butane, and heavier as liquid hydrocarbons, while the C_3^+ GPM considered the propane, butane, and heavier as liquid hydrocarbons.

4.2. Natural Gas Valorization

4.2.1. GPM and Flowrate Analysis

For this study, gas is considered rich when its GPM is equal to or higher than 3 gal/Mscf. On the other hand, for a lower value, the gas is considered lean. Additionally, the associated gas is considered of commercial interest when its gas production is higher than 10 million standard cubic feet per day (MMscfd). However, other commercial applications can be possible with lower flowrates.

4.3. Liquefied Natural Gas Production Feasibility

4.3.1 Technical Processing Analysis

The technical analysis was developed, taking into account the available techniques for gas treating and processing. Feed gas conditions and design characteristics considered were flowrates, gas composition, heavy hydrocarbons contents, water contents, gas acid compositions, inlet pressure conditions, the products desired, and the different technology available. Note that, since the water content is not reported in chromatographic analysis, for this study, it is assumed that the feed stream gas is water saturated at the plant inlet conditions. Additionally, for the technical proposal, conventional processes (using mature and proven technologies) were selected in each stage of the gas plant.

4.3.2 Economic Feasibility Study

For this work, the economic feasibility study is a class V study, which considers the preliminary analysis of the capital expenditure (CAPEX), and the economic balance analysis.

4.3.2.1. Capital Expenditure (CAPEX)

The capital expenditure of the different sections of the gas processing plant considered the previous technical process analysis and some other design and economic factors. For instance, to meet the best engineering design criteria, by overdesign, the inlet flowrate was incremented by 20 % of the actual flowrate to get a higher operational range. In the same way, all the resulting costs for the units were estimated with the economic approach introduced by Tannehill and Chandra [48]. The cost data are a proper approximation for the first estimated capital cost of a gas processing plant and came from consensus values from several engineering firms and actual plant cost data [25,48]. The premises and assumptions used for this analysis are shown in Table A.2 (Appendix A). Besides, the data apply only to new facilities (not applicable for retrofits or used equipment), and the costs are based on U.S. dollars.

The technical and economic proposal for the gas processing plant considers different equipment and conditions in each stage of the plant. Specifically, for the plant installation cost, the following assumptions were considered:

- **Gas sweetening:** In this section, the cost applies to remove the acid gases with DEA used as a solvent and an operating pressure from 585 to 785 psia. However, the cost excludes any gas dehydration after gas treating.

- **Gas dehydration:** In this section, to remove the water, the cost applies for new glycol dehydration (TEG) facility, having BTEX containment equipment, and for an operating pressure from 585 to 785 psia. However, the cost excludes improvements to generate concentrations of lean glycol greater than 98.6 wt %.

- **Natural gas liquids recovery:** In this section, to recover a single NGL product stream, the cost applies for a straight refrigeration process, including limited storage, the use of ethylene-glycol injection for hydrate inhibition, the cost of glycol regeneration. However, the cost excludes upstream compression and treating, liquid product fractionation, and any outlet-gas compression (pressure drop is small in this unit).

- **Natural gas liquid fractionation:** For this section, the most conventional fractionation process was considered. Furthermore, due to the lack of public data of fractionation cost, the cost for this stage was calculated as 50 % of the natural gas liquids recovery stage.

Note that within the battery limit of the gas plant, the infrastructure costs for gas gathering and inlet compression were not considered.

The first estimated capital cost of a gas processing plant excludes certain associated expenses and other contingencies. The authors suggest that these excluded costs represent an additional value of 25 to 40 % of the total cost. Therefore, for this work, to cover most of the required annexes costs and contingencies, the excluded cost represents an additional cost of 40 % of the total cost of the plant. Additionally, for obtaining a current preliminary estimate cost of the plant, the costs of the equipment were updated from 2017 to the present year by the use of the

Chemical Engineering Plant Cost Index (CEPCI), which gives a general estimate, according to Eq. (2)

$$Cost\ 2021 = \frac{Index\ value\ at\ present\ year}{Index\ value\ in\ 2017} * Cost\ 2017 \qquad (2)$$

The CEPCI for the first half of 2021 was 655.9, while the CEPCI for 2017 was 567.5.

4.3.2.2. Economic balance

The economic balance of the gas processing plant was carried out under some essential considerations. The inlet flowrate of the process was the average flow of the usual field flowrate production. In the same way, the economic values of the raw and processed materials were taken from the expected prices of the industry. Besides, the prices of natural gas liquids were contrasted and analyzed from the national and international markets. This consideration is because, in the Ecuadorian market, NGL (such as LPG) are subsidized, and prices do not correspond to the actual value. Also, the operational time of the SA Gas plant was established as 330 days per year, being an accurate time of the actual operating time of the industrial plants.

The processing cost represents all the total required expenses to maintain the plant working. In some cases, it is called OPEX, which means the operational expenditure needed to maintain a project running [28]. The gas processing costs are generally defined as dollars per thousand standard cubic feet of the gas processed (USD/Mscf). For this document, the OPEX includes all the expenses related to the production, such as supplies, power energy, equipment maintenance, and also residual gas treatment. However, it does not include the costs of labor (workers' wages and insurance) required to maintain the gas processing plant.

CHAPTER V

RESULTS AND DISCUSSION

5.1. Natural Gas Analysis in the Amazon Region

In the Amazon region, most of the fields produce associated gas as a by-product of hydrocarbon operations. The compositions and operating conditions of the associated gases are different from field to field. Therefore, it is essential to obtain and process actual data about the gas properties to evaluate the possible opportunities that associated gas can bring to the Ecuadorian industry.

Typically, in Ecuador, the hydrocarbon companies value more free gas than associated gas for industrial applications. However, the current production of free gas is not significant in the country. On the other hand, the associated gas produced is considerable, but it is not fully valorized. Besides, the products that could be obtained from associated gas processing are widely needed in the domestic market. In the same way, the associated gas is usually related to rich gas production due to the heavy hydrocarbon content linked to crude oil extraction. The processing of rich gasses is attractive for industry because they can produce more valuable products than lean gas processing [4].

Table 5 shows the compositions and operating conditions of associated gas produced along the Amazon region. By a brief overview of this data, the associated gas from Amazon is low in methane, but the heavy hydrocarbon content is significant. Thus, this gas could be used for hydrocarbon liquids recovery and fractionation. The flowrate of each field is also significant to be considered for industrial and commercial applications. However, the geographical scattering of the different hydrocarbon fields limits and hinders the installation of centralized associated gas processing systems in the Amazon region.

***Table 5**. Associated gas in the Amazon region*

Components	Mole Percent (mole %)										
	ITT Gas	**EY Gas**	**OY Gas**	**LA Gas**	**PA Gas**	**SH Gas**	**CU Gas**	**LI Gas**	**AU Gas**	**SA Gas**	**IN Gas**
C_1	45.01	30.93	71.19	55.87	3.82	37.10	14.56	25.97	55.22	58.54	38.58
C_2	4.91	5.31	9.55	11.80	1.40	10.53	4.27	9.34	9.36	10.54	6.56
C_3	4.97	7.41	9.05	14.78	4.76	16.48	11.56	17.13	14.46	13.77	9.35
i-C_4	0.97	1.72	1.90	2.07	1.16	2.66	2.37	2.37	2.81	4.43	2.41
n-C_4	2.02	2.73	2.22	4.64	2.94	6.75	5.38	6.92	4.94	0.00	1.40
i-C_5	0.61	0.96	0.62	1.11	1.21	1.98	1.88	2.22	1.47	0.82	0.91
n-C_5	0.51	0.70	0.39	1.11	1.51	2.24	1.99	2.69	1.30	**(-)**	0.10
i-C_6	**(-)**	0.15	**(-)**	**(-)**	0.60	0.83	0.74	1.08	0.24	**(-)**	**(-)**
n-C_6	**(-)**	**(-)**	0.41	0.95	0.83	1.16	0.91	1.53	0.28	**(-)**	0.44
i-C_7	**(-)**	0.03	**(-)**	**(-)**	0.56	0.44	0.35	0.55	0.23	**(-)**	**(-)**
n-C_7	**(-)**	**(-)**	0.56	**(-)**	**(-)**	0.12	0.09	0.12	0.05	**(-)**	**(-)**
N_2	30.51	5.94	0.73	2.09	1.13	2.65	1.81	1.82	3.82	2.55	4.81
CO_2	10.49	44.12	3.36	5.58	80.07	17.06	54.09	28.27	5.82	9.35	35.44
Pressure (psia)	128.70	112.70	54.70	39.70	64.20	40.45	38.70	45.20	40.95	39.70	64.70
Temperature (°F)	161.00	130.00	80.00	84.00	189.05	129.61	142.52	153.77	119.66	84.00	160.00
Flowrate (MMscfd) [49]	1.86	4.67	0.95	5.74	8.52	20.04	5.09	8.93	9.20	14.60	4.11
Source:	[50]	[51]	[52]	[42]	[53]	[53]	[53]	[53]	[53]	[54]	[55]

ITT Gas: Tiputini **EY Gas:** Edén Yuturi **OY Gas:** Oso Yaralpa **LA Gas:** Lago Agrio **PA Gas:** Palo Azul **SH Gas:** Shushufindi **CU Gas:** Cuyabeno **LI Gas:** Libertador **AU Gas:** Auca **SA Gas:** Sacha **IN Gas:** Indillana

Notes: (-) : Data not reported

Note that most of the fields have a medium and low pressure (<130 psia), and a temperature above room temperature (>60 ºF). Besides, no data is reported about the H_2S content. However, the carbon dioxide amount is relevant in some fields, implying the technical need for a gas sweetening stage in the possible gas valorization. Furthermore, no data is reported about the H_2O content, but it can be assumed as a water-saturated gas stream, implying the technical need for a gas dehydration stage in the possible gas valorization.

The amount of liquids in the gas is critical to determine the commercial applications. Consider that a gas stream with a higher GPM value has a more extensive availability to recover liquids. Therefore, this parameter is essential to make an accurate valorization of this resource. All this analysis will be highly developed in Section 5.2.

5.2. Associated Gas Valorization in the Amazon Region

The GPM analysis is crucial to identify the quality of a gas stream. A deep analysis of the associated gas in the Amazon region shows that most of the fields produce rich gases (considering that a rich gas has a GPM $\geq$ 3 gal/Mscf, otherwise is lean gas). Figure 17 presents the GPM C_2^+ and C_3^+ in the different fields in this region. The fields that attract the most attention are LA Gas, SH Gas, LI Gas, CU Gas, AU Gas, and SA Gas due to their high composition in C_2^+. They could be a potential source of hydrocarbon liquids recovery, specifically for ethane recovery. In the same way, those fields have the highest quantity of C_3^+ components, which can be used for propane and heavier hydrocarbon recovery. In this sense, LPG production can be potentially feasible. However, other parameters need to be considered for accurate valorization.

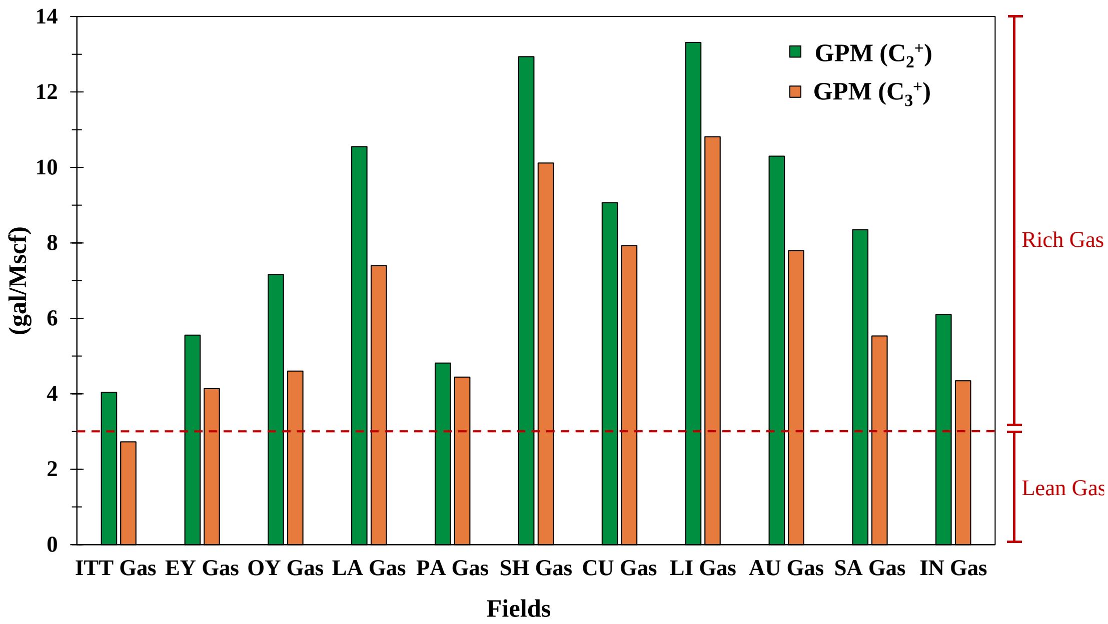

Figure 17. *GPM C_2^+ and C_3^+ in the Amazon region*

As noted above, the associated gases from the Amazon region are characteristically rich, and the opportunities for natural gas liquids recovery are appreciable. The level of GPM in a gas stream is essential but not the only aspect to consider when a gas valorization is carried out. Another critical parameter is the gas flowrate, being indispensable for meeting the commercial criteria values. Thus, a higher gas flowrate is most commercially appreciated, and it must be directly related to the GPM value. Figure 18 shows the associated gas GPM and its flowrate in the region studied (considering that an associated gas stream with $Q \geq 10$ MMscfd is of commercial interest).

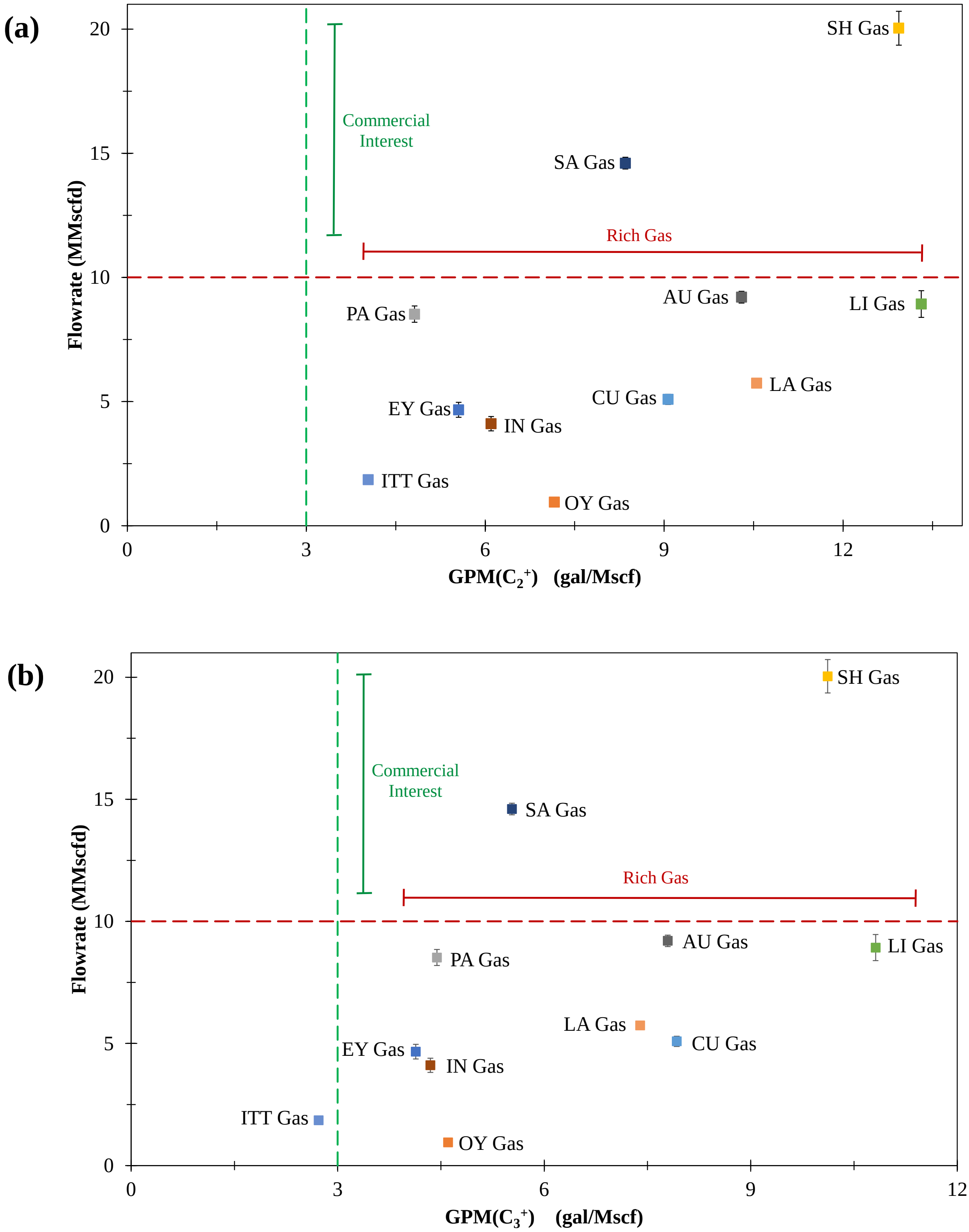

Figure 18. *Associated gas flowrate and GPM in the Amazon region. (a) GPM based upon C_2^+, (b) GPM based upon C_3^+*

The graphs simplify interesting aspects to obtain a possible gas valorization. For the case of a flowrate and GPM over 10 MMscfd and 3 gal/Mscf, respectively, the associated gas production is located in a zone of rich gases with high commercial interest. It implies that these gases can potentially be used to recover natural gas liquids. For the case of a flowrate over 10 MMscfd, but with GPM less than 3 gal/Mscf, the associated gas continues being in a zone of commercial interest. However, as it is a lean gas, it cannot be used for NGL recovery, but it can be used for power generation because of its methane content. For the case of a flowrate less than 10 MMscfd, but with a high content of liquids (over 3 gal/Mscf), a deep analysis is required to identify the feasibility of gathering and its commercial value. On the other hand, for those lean gases with a flowrate of less than 10 MMscfd, treatment must be needed for their later disposal to the environment.

The most industrial attractive associated gases were those rich gases with a high commercial value. They were gases from the Shushufindi field (SH Gas) and Sacha field (SA Gas). However, for obtaining a proper valorization, it is indispensable to analyze the current uses of these gases. In the Amazon region, just a few quantities of associated gas produced are used by the industry. For instance, the *Shushufindi* gas plant principally uses the associated gas from SH Gas, LI Gas, and LA gas to produce LPG and natural gasoline. On the other hand, SA Gas is minor used by the Optimization of Power Generation and Energy Efficiency project (OGE&EE) (see further information of the OGE&EE project in Figure A.1, Appendix A). Therefore, it is essential to valorize SA Gas to produce natural gas liquids and, thus, avoid flaring and wasting resources.

According to the hydrocarbon reserves reported for SA Gas [47] and its current gas production [49], the associated gas produced in this field will be approximately 64,778 MMscf during the next twelve years. This quantity may even increase because of the new hydrocarbon drilling and extraction projects in the field. One of the potential uses of SA Gas, due to its high heavy hydrocarbons content and its commercial flowrate, is LPG production. The last alternative will significantly impact the current Ecuadorian LPG market and the national economy because of the low LPG production and high expenses that represent the imports of this commodity. To obtain LPG from the associated gas, first is necessary the SA Gas treating and processing. It involves different processing stages such as acid gas removal, water removal, liquids condensation, and liquids fractionation, which are discussed in Section 5.3.

5.3. Liquefied Petroleum Gas Production Feasibility

The production of associated gas in the Amazon region needs to be considered a crucial national energy source. Therefore, the following section discusses the feasibility of gas valorization for liquefied petroleum gas production from a technical and economic perspective.

The gas processing techniques and economy depend on the feed conditions and processing specifications. These parameters highly influence the technology selected and unit configuration for the gas plant. Table 6 shows the feed gas conditions and processing specifications considered for this work to produce LPG from the associated gas from the Sacha field

Table 6. *Feed SA Gas conditions and processing specifications*

Feed SA Gas Conditions	
Components	mole %
C_1	58.54
C_2	10.54
C_3	13.77
i-C_4	4.43
n-C_4	0.00
i-C_5	0.82
N_2	2.55
CO_2	9.35
Pressure (psia)	39.70
Temperature (°F)	84.00
Flowrate (MMscfd)	14.60
GPM C_3^+	5.5
C_3^+ Gas Content	19 mole %
SA Gas Processing specifications	
Separation Efficiency (C_3^+)	90 %

Note that the ethane content in SA Gas is significant (10 %); however, trying to recover it implies higher costs than propane and butane recovery. Besides, ethane extraction also requires fixed customers in an established market.

5.3.1. Technical Processing Study

By treating and processing the gas from the Sacha field (with the current flowrate of 14.6 MMscfd and GPM C_3^+ of 5.5 gal/Mscf), the potential LPG production is 1,731 barrels per day (148.78 Ton/day), implying an increase of around 10,000 LPG cylinders of 15 kg per day in the national LPG market, as seen in Figure 19. This production could easily supply nearly 150,000 households monthly in Ecuador (considering that residential LPG cylinders typically are used twice a month in a household). Furthermore, there is the possibility to process 10.9 MMscfd of residual gas to meet sale market specifications and obtain more revenues.

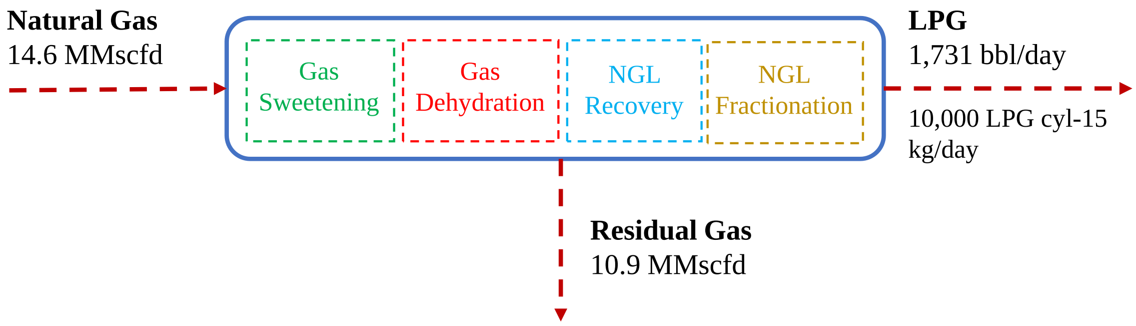

Figure 19. *Value chain and potential production of SA Gas processing plant*

The principal stages of a natural gas processing plant proposal are gas sweetening, gas dehydration, NGL recovery, and NGL fractionation. The main products will be liquefied petroleum gas, residual gas, and natural gasoline as a by-product of the plant operations. The technology applied in each section mainly depends on the conditions of the raw gas that is treated and the desired products. Thus, the following analysis centers on each section of a gas processing plant, reviewing the technology available for SA Gas industrialization.

Gas sweetening: In the gas sweetening stage, the available technology (liquid-phase absorption) for removing acid gases includes chemical, physical and hybrid solvents. The use of each of them depends on different parameters, including the type and amount of acid gases, hydrocarbon composition, partial pressure in the feedstock, and others. SA Gas is characterized by a high quantity of natural gas liquids due to its GPM of 5.5. Physical solvents are not possible for this situation because, according to Gas Processors Suppliers Association (GPSA) [30], physical solvents tend to dissolve heavy hydrocarbons. Additionally, to remove around 9.35 mole % of CO_2 (and considering possible H_2S removal at the same time) is necessary an intensive not selective acid gases removal. According to Kidnay and Parrish [18], the chemical solvents meet these requirements and partially remove COS and mercaptans. (Chemical solvents also are favorable for low partial pressures of the acid gases). Therefore, a possible technology for this stage is chemical solvents, specially diethanolamine (DEA), one of the most matured technologies of chemical solvents.

Gas Dehydration: As a result of amine usage (in water solution), the treated gas leaves saturated with water. In the gas dehydration stage, it is necessary to remove this water content. The conventional technologies for water remotion include absorption and adsorption methods. For selecting each of them, several factors must be considered. As this process is not focused on cryogenic liquids recovery, adsorption methods such as molecular sieves are not considered. According to Kidnay and Parrish [18], molecular sieve dehydration requires high energy consumption in the regeneration step.

On the other hand, absorption methods such as glycol dehydration (TEG) are more feasible to meet the specifications of this process. According to Mokhatab et al. [24], glycol dehydration is more economically expensive in capital and operating expenditure than molecular sieves technology and also can meet the specification for NGL recovery as low as -40 ºF. Therefore, a possible technology for SA Gas to remove water is glycol technology, especially the triethylene glycol (TEG) dehydration process. In addition, according to Myers, it is also required to include a BTEX containment unit [56]. This equipment avoids the absorption of BTEX hydrocarbons (benzene, toluene, ethylbenzene, and xylenes) in the TEG process and their subsequent release to the atmosphere in the glycol regenerator.

Natural gas liquids recovery: A chart presented by Kidnay, Parrish, and McCartney [25] (Figure B.1 Appendix B) shows the ethane and propane recovery level dependency as a function of the C_3^+ content in the feed stream and the separation temperature. It is noticeable that recovery levels increase with a higher richness of the gas. For a 5.5 GPM C_3^+ gas, a 90 % propane recovery requires approximately -30 to -40 ºF, at 614.7 psia. Furthermore, there is also a chance of high ethane recovery from SA Gas through different refrigeration techniques arrangement and combination. It also could increase the propane and butane recovery to almost 100 % (Figure B.2 Appendix B). However, ethane recovery, which requires separation temperatures lower than 40 ºF (cryogenic temperatures), is not the scope of this work, but it could be considered for future projects.

For recovering NGL products, there are several refrigeration techniques, including valve expansion, mechanical refrigeration, and turboexpanders. Their use depends on different factors such as the desired products, the inlet conditions, the economic availability, and others. As this process is not focused on cryogenic recovery, which requires low temperatures for liquids condensation (-150 ºF), turboexpanders are not considered because of their high operation cost [24]. Also, despite its simplicity in operation and low maintenance equipment, J-T units require high inlet pressures that SA Gas does not have. Therefore, a possible technology for NGL recovery, in this case, is mechanical refrigeration (straight refrigeration) which can meet the actual low inlet gas pressure conditions.

Furthermore, according to GPSA, straight refrigeration is quite flexible because it can be used for modest liquid recovery, high propane recovery (-40 ºF), and reasonable quantities of ethane recovery (in the case of rich gases) [30]. For this process, an ideal system is mechanical refrigeration with propane, which is also an industry matured technology. Besides, according to Kidnay et al. [25], ethylene glycol injection is also necessary for hydrate inhibition in this section (when the water content is higher).

Natural gas liquid fractionation: In the gas fractionation stage, the conventional technology is considered for processing the raw NGL into individual products by fractionation. The NGL goes through a four-column fractionation system. It consists of a deethanizer unit, a depropanizer unit, a debutanizer unit, and a butane splitter unit; that processes the gas from raw NGL into end products such as LPG and natural gasoline.

Within this work's associated gas value chain, Figure 20 summarizes the above analysis of the potential technologies that can be applied in the different SA Gas processing stages.

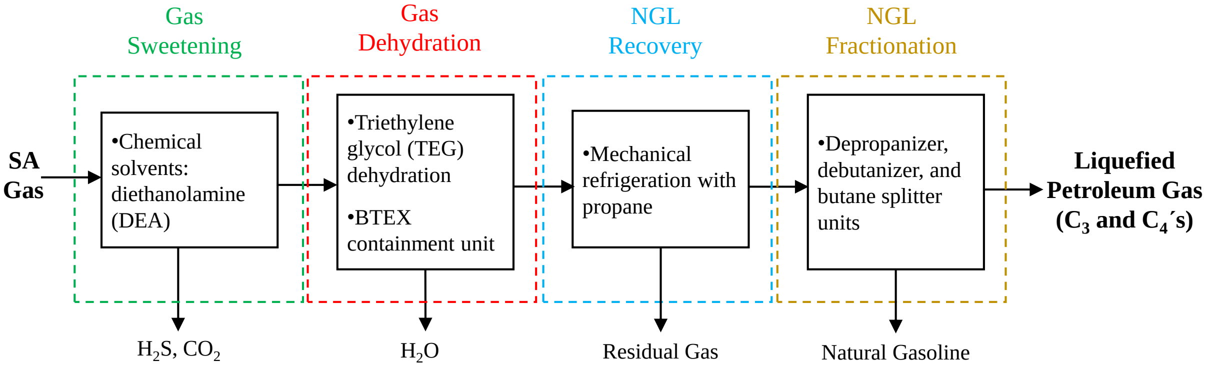

Figure 20. *Technology selection for SA Gas processing: a proposal*

The technical analysis of the gas processing plant proposal must be accompanied by an economic analysis. Thus, the following section reviews economic factors of the associated gas valorization from Sacha field as Liquefied Petroleum Gas.

5.3.2. Economic Feasibility Study

An economic point of view in the industry is essential to focus investments in different projects. Therefore, in the next section, various factors are analyzed for the economic feasibility of the SA Gas processing plant.

5.3.2.1. Plant Installation Cost

The plant installation cost represents the total budget to build and startup the industrial gas plant. In some cases, it is called CAPEX, which means the capital expenditure needed to start a project, in this case, to build the plant [28]. Since gas flowrate can vary in the field, to build the infrastructure is necessary to consider the overdesign engineering capacity. Thus, the flowrate for SA Gas processing plant design is 17.5 MMscfd. The expenses for each section are detailed below:

Gas Sweetening: In the gas sweetening stage, the aim is to remove the acid gases from the SA Gas stream. Hence, it is necessary to remove approximately 9.35 % of acid gases. Figure C.1 (Appendix C) shows the capital cost required to remove this amount of gases using DEA as a function of plant capacity. The acid gases volume to remove are directly related to their operating and capital cost. Large removal volume implies high capacities (absorber and regenerator) to manage the amine recirculation rates. Thus, it requires higher costs. In this study, the estimated capital cost for SA Gas sweetening, using DEA as a solvent, is approximately 1.16 MMUSD.

Gas Dehydration: In the gas dehydration stage, the aim is to remove the water contents from the SA Gas stream. Figure C.2 (Appendix C) shows the capital cost required to remove water using Glycol Dehydration as a function of plant capacity. As gas is water-saturated, the dehydration capital and operation cost depend on the feed gas flowrate. For SA Gas dehydration, it is necessary approximately 0.29 MMUSD as the capital cost for a gas dehydration facility using TEG technology.

Natural gas liquids recovery: In natural gas liquids recovery, the aim is to condense the heavy hydrocarbons from the SA Gas stream. Figure C.3 (Appendix C) shows the capital cost for a straight refrigeration process to NGL recovery. Note that the increase in the GPM (on a C_3^+ basis) impacts the recovery cost, mainly because of the bigger load of refrigeration required. Hence for SA Gas, with a GPM of 5.5, the capital cost for the NGL recovery facility is approximately 5.78 MMUSD.

Natural gas liquid fractionation: In the natural gas liquids fractionation stage, the aim is to separate the NGL from SA Gas into individuals. For this study, the estimated capital cost for NGL fractionation is 2.89 MMUSD.

Figure 21 summarizes the CAPEX for the SA Gas processing plant in a million dollars for the current year. The budget expenses are presented in Table C.1.

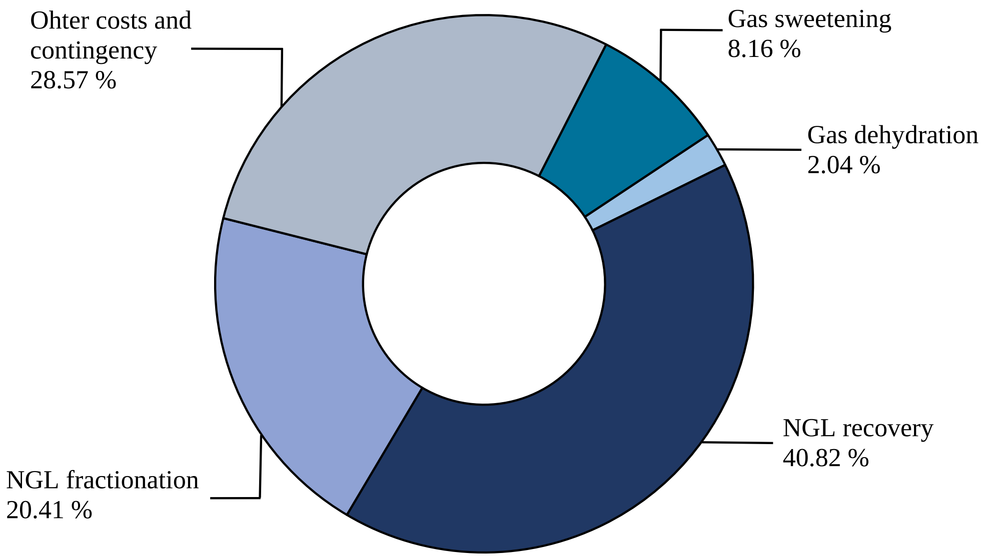

Figure 21. *Estimated costs (class V) for SA Gas processing plant in 2021*

The estimated cost (class V) for the SA Gas processing plant is 14.6 MMUSD. However, for an accurate approximation of the first capital cost estimate, the cost must consider local conditions (Ecuadorian market), such as transportation, taxes, and national insurance. For this study, the local considerations will increase 50 % to the estimated capital cost. Thus, the CAPEX for the gas processing plant considering local conditions is 21.9 MMUSD.

Finally, an essential factor in economic studies is the estimated time for construction because it affects planning, revenue, tied-up capital, and interest cost. For the case of this study, and according to [25], the construction tome for the SA Gas processing plant will take around 18 months (construction time required for plants smaller than 200 MMscfd).

5.3.2.2. Economic Balance Analysis

An economic balance study of the gas processing plant is indispensable to recognize the revenues and investment return. It will help to decide if a project is whether profitable or not. Besides, it is vital to determine the different incomes and outcomes of the gas plant. There are different monetary values related to the SA Gas processing plant; each varies according to the location, politics, and international environment. Thereby, Table 7 shows the raw natural gas price, processing cost, and natural gas liquids price considered for this study.

Table 7. Economic values for the balance analysis

	Value	Unit	Source
Natural Gas price*	2.94	USD/MMBTU	[57]
Natural Gas Processing cost†	1.5	USD/Mscf	[58]
Liquefied petroleum gas price‡	46.62	USD/bbl	[59]

Notes: * Henry Hub Natural Gas Spot Price for the second quarter of 2021.
† Referential value with refineries operating cost in Ecuador, assuming a post residual gas conditioning.
‡ Import LPG price (international price) reported from Petroecuador for the second quarter of 2021.

It is important to know that the prices tend to change constantly. Thus, the economic balance is based on the prices for the second quarter of 2021. Given these parameters, a simplified flow sheet of SA Gas processing plant economy is shown in Figure 22. The expenses "E" represents the cost for purchasing raw natural gas (14.69 MMUSD/year). "C" represents the total processing cost of the gas plant (7.23 MMUSD/year). On the other hand, "I" represents the total income due to the sales of liquefied petroleum gas and treated residual gas in the market at international prices (37.66 MMUSD/year). An overall balance shows a gas plant profit of 15.74 MMUSD per year, which indicates a profitable project, taking advantage of the associated gas from Sacha field in the Amazon region instead of flaring it.

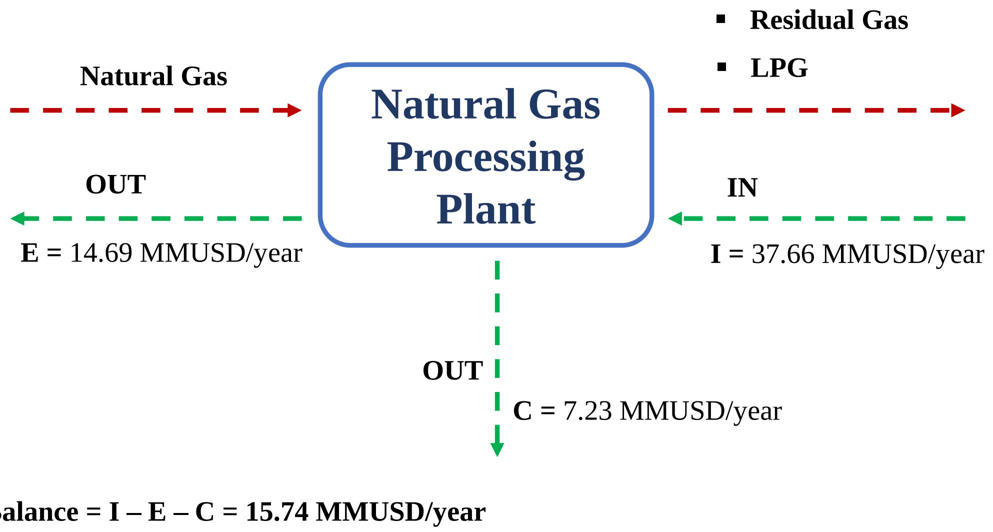

Figure 22. *Simplified economic balance for SA Gas processing plant considering an international market. The solid and dashed lines represent raw material (or processed) and their related costs, respectively*

Nevertheless, notice that natural gas and liquefied petroleum gas are considerably subsidized in Ecuador [60]. The current subsidized price for natural gas is 2 USD/MMBTU [61,62], whereas the LPG subsidized price is 0.106 USD/kg (9.17 USD/bbl) [63]. Hence, Figure 23 shows the different balance scenarios for the SA Gas processing plant considering the domestic and international markets. Note that, because of the hydrocarbon subsidies, the 15 kg cylinders should cost 2.97 USD instead of the subsidized price (1.60 USD) for an equilibrium economy at the gas plant in the local market.

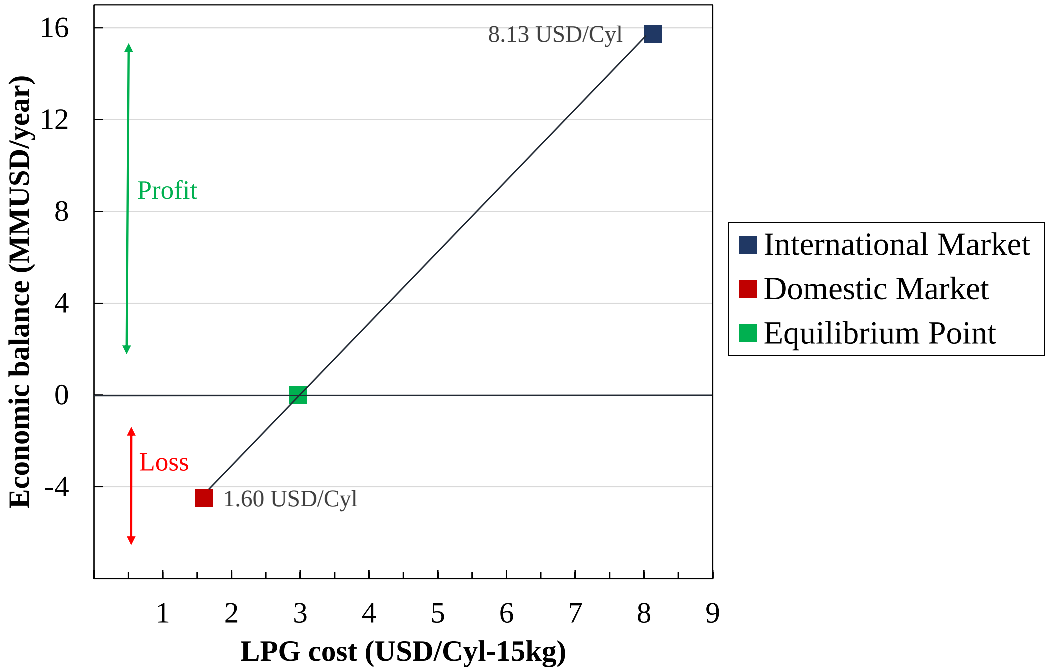

Figure 23. *Economic balance considering possible scenarios*

However, considering the domestic market, by processing 14.6 MMscfd of the associated gas from the Sacha field in the Amazon region, the potential LPG production could be 1,731 bbl/day. An amount representing approximately 30 % of current national LPG production and 14.5 MMUSD/year in commodity imports. Figure 24 shows the cost of introducing 1,731 bbl/day to the national LPG market through regular imports and the SA Gas processing plant. Despite the significant local hydrocarbon subsidies, the opportunity cost of national LPG production is 10.02 MMUSD/year to the Ecuadorian economy, being an alternative more viable economically than the net LPG import option. Thus, the investment cost would be justified.

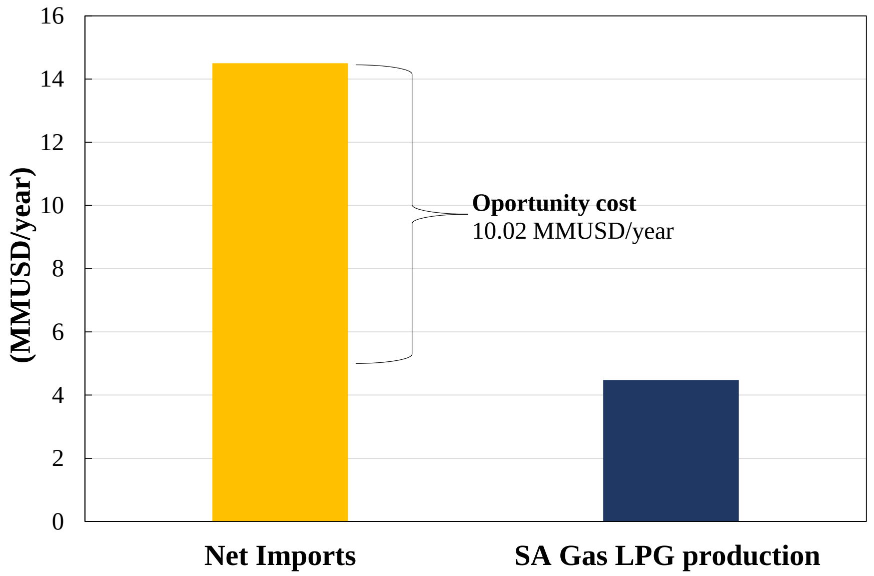

Figure 24. *Cost of introducing 1,731 barrels per day to the domestic LPG market*

The insertion of 1,731 bbl/day of LPG into the domestic market (through the associated gas valorization) would highly reduce the import dependency on this commodity. Besides, the associated gas valorization would represent a great social impact by introducing ~10,000 LPG cylinders of 15 kg per day to the domestic market. It also could reduce the environmental and social impact that implies gas flaring. Nevertheless, note that other fields also present commercial characteristics to be analyzed for industrial valorization opportunities. Figure 25 illustrates the final proposal for the SA Gas processing plant.

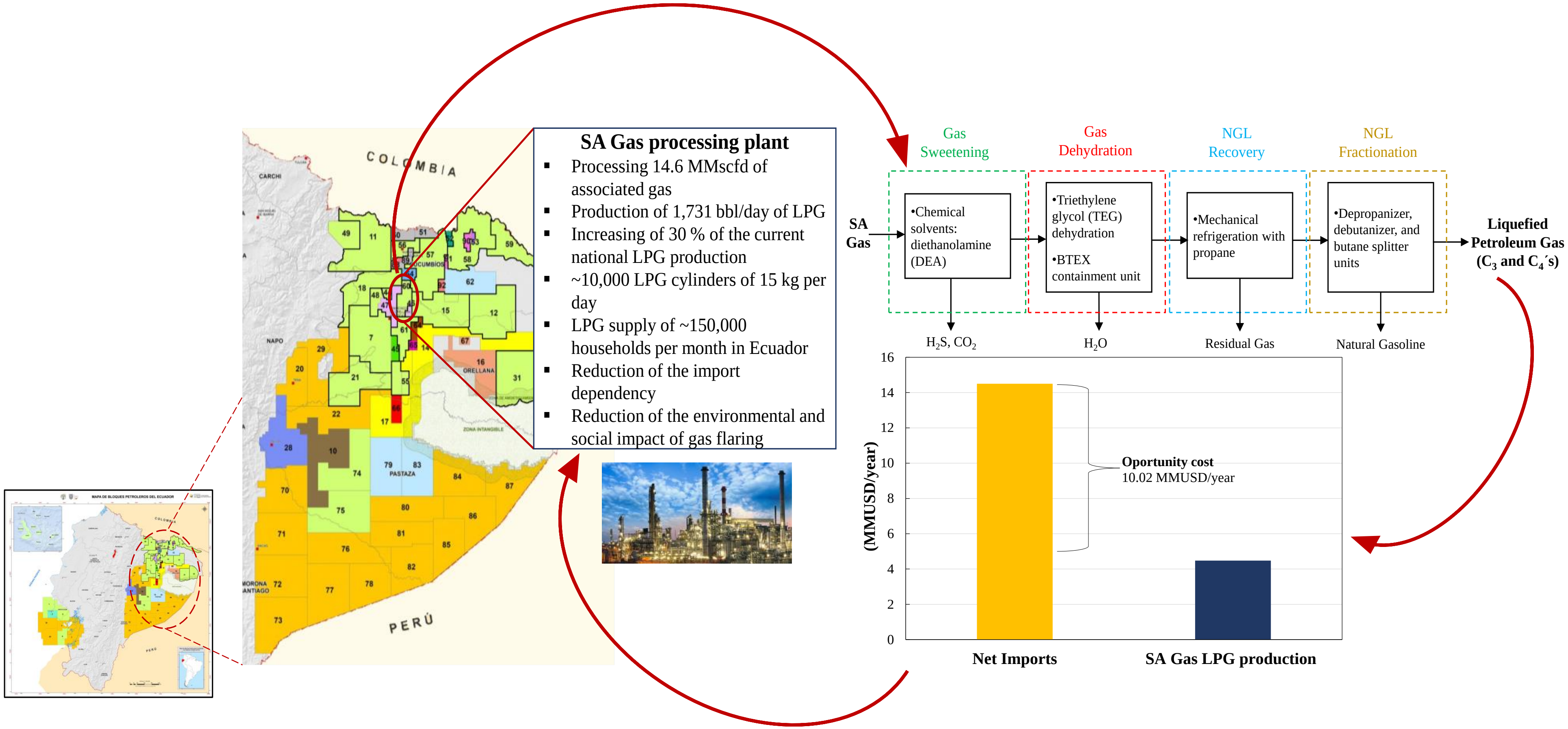

Figure 25. *SA Gas processing plant: final proposal*

CONCLUSIONS AND RECOMMENDATIONS

- In the Amazon region, the associated gas produced has a high content of heavy hydrocarbons (GPM $C_2^+ \geq 3$ gal/Mscf and GPM $C_3^+ \geq 3$ gal/Mscf) and commercial characteristics. Therefore, there is an opportunity to take advantage of this gas by natural gas processing, increasing industrial revenues, and reducing gas flaring.

- The processed gas from the Sacha field could produce 1,731 bbl/day of LPG, which constitutes an increase of 30 % of the current national LPG production. This associated gas valorization would represent a great social impact by introducing ~10,000 LPG cylinders of 15 kg per day to the domestic market. It easily could represent the LPG supply of nearly 150,000 households per month in Ecuador. The insertion of this amount of LPG into the domestic market would highly reduce the import dependency on this commodity.

- The technical analysis determined that the potential technology to process the associated gas from the Sacha field includes gas sweetening, dehydration, natural gas liquids recovery, and fractionation units.

- The economic study (class V) showed that the estimated capital expenditure (CAPEX) of the gas processing plant for SA Gas is 21.9 MMUSD, considering local conditions. The plant consists of gas sweetening, dehydration, recovery, and fractionation stages.

- The economic balance study of the SA Gas processing plant showed that the introduction of 1,731 bbl/day of LPG would replace 14.5 MMUSD/year in LPG imports. The opportunity cost of producing this amount of LPG would give the Ecuadorian economy a profit of 10.02 MMUSD/year.

- An economic study of the associated gas compression, gathering process, and related infrastructure is recommended to have a more accurate value of the CAPEX of the gas processing plant. In addition, it is required to estimate the costs of labor (workers' wages and insurance) to have a better perspective of the economy of the gas processing plant.

- It is recommended, for future work on this topic, a deep analysis of the associated gas produced in the different wells of the Amazon region to select more flexible equipment with a minimum operating range to process the gas.

REFERENCES

[1] A. Bahadori, *Natural Gas Processing. Technology and Engineering Design*. Oxford: Gulf Professional Publishing, 2014. ISBN: 978-0-08-099971-5

[2] BP plc, "Statistical Review of World Energy 2021 | 70th edition," 2021. [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.

[3] K. M. ElBadawy, M. A. Teamah, A. I. Shehata, and A. A. Hanfy, "Simulation of Liquefied Petroleum Gas (LPG) Production from Natural Gas Using Fractionation Towers," *Int. J. Adv. Sci. Tech. Res.*, vol. 6, no. 7, 2018, doi: 10.26808/rs.st.i7v6.16.

[4] R. Hubbard, "The Role of Gas Processing in the Natural-Gas Value Chain," *J. Pet. Technol.*, vol. 61, no. 08, pp. 65–71, Aug. 2009, doi: 10.2118/118535-JPT.

[5] J. G. Speight, *Natural gas: A basic handbook*, 2nd ed. Cambridge: Elsevier, 2019. ISBN: 9780128095706

[6] EP Petroecuador, "Informe Estadístico Enero-Diciembre 2020," Jan. 2021. Accessed: Aug. 06, 2021. [Online]. Available: https://www.eppetroecuador.ec/wp-content/uploads/downloads/2021/03/INFORME-ESTADISTICO-DICIEMBRE-2020.pdf.

[7] EP Petroecuador, "Plan Estratégico Empresarial 2018-2021," 2020. Accessed: Aug. 06, 2021. [Online]. Available: https://www.eppetroecuador.ec/wp-content/uploads/downloads/2021/04/Plan-Estratégico-2018-2021-actualización-2020.pdf.

[8] EP Petroecuador, "Rendición de Cuentas 2020," Quito, May 2021. Accessed: Aug. 07, 2021. [Online]. Available: https://www.eppetroecuador.ec/wp-content/uploads/downloads/2021/06/INFORME-RENDICION-DE-CUENTAS-2020-EP-Petroecuador.pdf.

[9] S. Mokhatab, W. A. Poe, and J. G. Speight, *Handbook of Natural Gas Transmission and Processing*. Oxford: Gulf Professional Publishing, 2006. ISBN: 13: 978-07506-7776-9

[10] The World Bank, "Seven Countries Account for Two-Thirds of Global Gas Flaring," Apr. 28, 2021. https://www.worldbank.org/en/news/press-release/2021/04/28/seven-

countries-account-for-two-thirds-of-global-gas-flaring (accessed Jul. 27, 2021).

[11] C. D. Elvidge, M. Zhizhin, K. Baugh, F.-C. Hsu, and T. Ghosh, “Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data,” *Energies 2016, Vol. 9, Page 14,* vol. 9, no. 1, p. 14, Dec. 2015, doi: 10.3390/EN9010014.

[12] International Finance Corporation and The World Bank Group, “Environmental, Health and Safety Guidelines for Onshore Oil and Gas Development,” Apr. 2007. Accessed: Jul. 27, 2021. [Online]. Available: https://www.ifc.org/wps/wcm/connect/f0167aa2-edd2-4b46-aeb6-b2935a9e6c95/Final%2B-%2BOnshore%2BOil%2Band%2BGas%2BDevelopment.pdf?MOD=AJPERES&CVID=jkD2DAU&id=1323153172270.

[13] Global Gas Flaring Reduction Partnership and The World Bank Group, “Global Gas Flaring Tracker Report,” Washintong, Apr. 2021. Accessed: Jul. 27, 2021. [Online]. Available: https://thedocs.worldbank.org/en/doc/1f7221545bf1b7c89b850dd85cb409b0-0400072021/original/WB-GGFR-Report-Design-05a.pdf.

[14] The World Bank, “Global Gas Flaring Reduction. A Public-Private Partnership. A Voluntary Standard for Global Gas Flaring and Venting Reduction,” Washington, DC, May 2004. Accessed: Oct. 01, 2021. [Online]. Available: https://documents1.worldbank.org/curated/en/342761468780614074/pdf/295550GGF0a0pu1ship10no10401public1.pdf.

[15] Ministerio de Energía y Recursos Naturales No Renovables and Instituto de Investigación Geológico y Energético, “Balance Energético Nacional 2020,” 2021. [Online]. Available: https://www.recursosyenergia.gob.ec/wp-content/uploads/2021/09/Balance-Energético-Nacional-2020-Web.pdf.

[16] Petroamazonas EP, “Optimization of Power Generation and Energy Efficiency (OGE&EE),” Panamá, Sep. 2016. Accessed: Aug. 04, 2021. [Online]. Available: https://unfccc.int/files/focus/mitigation/application/pdf/laccf-nama-ogeee-ecuador.pdf.

[17] Petroamazonas EP, “Estudio de Impacto y Plan de Manejo Ambiental OGE&EE,” Jan. 2014. Accessed: Aug. 11, 2021. [Online]. Available: https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2014/04/Cap-4_Descripcin-del-Proyecto-OGEEE.pdf.

[18] A. J. Kidnay and W. R. Parrish, *Fundamentals of Natural Gas Processing*. New York:

Taylor and Francis Group, 2006. ISBN: 13: 978-0-8493-3406-1

[19] Carbon Limits AS., "Reduction of gas flaring in Ecuador and Peru Final report ," Oslo, Oct. 2017. Accessed: Aug. 04, 2021. [Online]. Available: https://rue.bmz.de/includes/downloads/2017_BGR-Study_GasFlaring_Ecuador_Peru.pdf.

[20] F. Facchinelli *et al.*, "Unburnable and Unleakable Carbon in Western Amazon: Using VIIRS Nightfire Data to Map Gas Flaring and Policy Compliance in the Yasuní Biosphere Reserve," *Sustainability*, vol. 12, no. 1, 2020, doi: 10.3390/su12010058.

[21] W. Diaz, "Target: zero flaring in Ecuador's Cuyabeno wildlife reserve," University of Calgary, Calagry, 2004.

[22] La Hora, "Corte acepta demanda de niñas para eliminar mecheros en Amazonía," Quito, Jan. 2021. Accessed: Aug. 24, 2021. [Online]. Available: https://lahora.com.ec/quito/noticia/1102339106/corte-acepta-demanda-de-ninas-para-eliminar-mecheros-en-amazonia.

[23] W. Bakar and R. Ali, "Natural Gas," in *Philosophical Transactions of The Royal Society B: Biological Sciences*, vol. 276, P. Pólocnik, Ed. InTech, 2010. ISBN: 978-953-307-112-1

[24] S. Mokhatab, W. A. Poe, and J. Y. Mak, *Handbook of Natural Gas Transmission and Processing: Principles and Practices*, Third Edit. Oxford: Gulf Professional Publishing, 2015. ISBN: 978-0-12-801499-8

[25] A. J. Kidnay, W. R. Parrish, and D. G. McCartney, *Fundamentals of Natural Gas Processing*, Third Edit. New York: Taylor & Francis Group, 2020. ISBN: 13: 978-1-138-61279-2

[26] S. Mokhatab and W. A. Poe, *Handbook of Natural Gas Transmission and Processing*, Second Edi. Boston: Gulf Professional Publishing, 2012. ISBN: 978-0-12-386914-2

[27] M. Wallin, "An Introduction to the Offshore Basics – Fire safety of a drillship, Drilling Rig Unit (DRU)," TURKU Unisversity of Applied Sciences, 2014.

[28] C. J. Cleveland and C. Morris, *Dictionary of Energy*, Second Edi. Amsterdam: Elsevier, 2015. ISBN: 978-0-08-096811-7

[29] U.S. Energy Information Administration (EIA), "Oil and petroleum products explained Offshore oil and gas," Dec. 07, 2020. https://www.eia.gov/energyexplained/oil-and-petroleum-products/offshore-oil-and-gas-in-depth.php (accessed Jul. 26, 2021).

[30] Gas Processors Suppliers Association (GPSA), "Engineering Data Book," Twelfth Ed., Tulsa: Gas Processors Suppliers Association, 2004.

[31] K. J. Morganti, T. M. Foong, M. J. Brear, G. Da Silva, Y. Yang, and F. L. Dryer, “The Research and Motor octane numbers of Liquefied Petroleum Gas (LPG),” *Fuel*, vol. 108, pp. 797–811, Jun. 2013, doi: 10.1016/J.FUEL.2013.01.072.

[32] A. Demirbas, “Fuel Properties of Hydrogen, Liquefied Petroleum Gas (LPG), and Compressed Natural Gas (CNG) for Transportation,” *Energy Sources*, vol. 24, no. 7, pp. 601–610, 2002, doi: 10.1080/00908312.2002.11877434.

[33] J. G. Speight, *Handbook of Natural Gas Analysis*. Hoboken: John Wiley & Sons, Inc., 2018. ISBN: 9781119240280

[34] Servicio Ecuatoriano de Normalización, “NTE INEN 675 Productos derivados del petróleo. Gas licuado de petróleo (GLP). Requisitos,” INEN, Quito, Ecuador, 675, 2017. Accessed: Aug. 03, 2021. [Online]. Available: https://www.normalizacion.gob.ec/buzon/normas/nte_inen_675-1.pdf.

[35] M. R. Echeverria Recalde, “Operational Improvements in the Shushufindi Gas Plant as an Alternative to Increasing the Availability of Liquefied Petroleum Gas (LPG) in the Ecuadorian Market,” Universidad de Investigación de Tecnología Experimental Yachay, Urcuquí, 2020.

[36] Petroamazonas EP, “Plan de Desarrollo-Campo Amistad,” *Campos Oil & Gas 2018*, Mar. 12, 2018. https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2018/03/CAMPOAMISTAD.pdf (accessed Aug. 04, 2021).

[37] Petroamazonas EP, “Memoria de Sostenibilidad ,” 2013. Accessed: Aug. 05, 2021. [Online]. Available: https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2014/12/MEMORIA_SOSTENIBILIDAD_PETROAMAZONAS_2013.pdf.

[38] Ministerio de Energía y Recursos Naturales No Renovables and Instituto de Investigación Geológico y Energético, “Balance Energético Nacional 2019,” 2020. Accessed: Aug. 08, 2021. [Online]. Available: https://www.recursosyenergia.gob.ec/wp-content/uploads/2020/12/Balance-Energetico-Nacional-2019-1.pdf.

[39] Instituto Ecuatoriano de Normalización (INEN), “NTE INEN 0111: 1998 Cilindros de acero soldados para gas licuado de petróleo GLP. Requisitos e inspección,” Quito, Ecuador, 0111, 1998. Accessed: Aug. 06, 2021. [Online]. Available: https://archive.org/details/ec.nte.0111.1998/page/n1/mode/2up.

[40] Briones Orellana; María Gabriela, “Estimación del costo de comercialización de los

cilindros de GLP en la CEM ‘Austrogas,’” Universidad de Cuenca, Cuenca, 2011.

[41] EP Petroecuador, “INFORME ESTADÍSTICO ANUAL 2019,” Quito, 2020. Accessed: Aug. 07, 2021. [Online]. Available: https://www.eppetroecuador.ec/wp-content/uploads/downloads/2020/11/INFORME-ESTADÍSTICO-ANUAL-2019.pdf.

[42] Pazos; James, “Optimización de la captación de gas natural y producción de GLP en los complejos petroleros del nororiente ecuatoriano,” Instituto de Altos Estudios Nacionales, Quito, 2008.

[43] EP Petroecuador, “Gerencia de Refinación: Capacidad Operativa de Refinerías,” Ecuador, Sep. 2019. Accessed: Aug. 07, 2021. [Online]. Available: https://www.eppetroecuador.ec/wp-content/uploads/downloads/2019/09/CAPACIDAD-DE-REFINERIAS-27-09-2019.pdf.

[44] Petroamazonas EP, “Listado Oficial de Nomenclatura Interna Para Facilidades de Producción, Activos, Bloques, Campos, Plataformas y Pozos de Petroamazonas,” Gerenciamiento de Datos & SIG, Dec. 2020. Accessed: Aug. 11, 2021. [Online]. Available: https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2020/12/GDD-PAM-RPR-LISTADO-OFICIAL-NOMENCLATURA-20201231.pdf.

[45] Petroamazonas EP, “Política de Estándares de Nomenclatura de Exploración y Operaciones,” Gestión Documental y Archivo - Tecnología de la Información, May 2011. Accessed: Aug. 11, 2021. [Online]. Available: https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2018/08/Políticas-de-Estándares-de-Nomenclatura.pdf.

[46] Ministerio de Energía y Recursos Naturales no Renovables, “Mapas Petroleros del Ecuador,” Feb. 2021. Accessed: Aug. 04, 2021. [Online]. Available: https://www.recursosyenergia.gob.ec/mapas/.

[47] Ministerio de Energía y Recursos Naturales No Renovables, “Informe anual de Potencial Hidrocarburífero del Ecuador 2018,” 2018. Accessed: Aug. 15, 2021. [Online]. Available: https://www.recursosyenergia.gob.ec/wp-content/uploads/2019/11/Informe-Anual-del-Potencial-Hidrocarburífero-del-Ecuador-2018.pdf.

[48] C. Tannehill and A. Chandra, “Budget Estimate Capital Cost Curves for Gas Conditioning and Processing - Updated 2018,” Tulsa, 2018. Accessed: Aug. 30, 2021. [Online]. Available: https://gpamidstream.org/publications/item/?id=4315.

[49] EP Petroecuador, “Producción Fiscalizada. Resumen Ejecutivo de Operaciones,” Jun. 2021. Accessed: Sep. 01, 2021. [Online]. Available: https://www.eppetroecuador.ec/?p=3721.

[50] M. López, “Optimización del Transporte de Crudo Pesado, Mediante la Implementación de un Sistema de Calentamiento de Fluido en el Campo Ishpingo-Tambococha-Tiputini (ITT),” Universidad Central del Ecuador, 2017.

[51] N. Sánchez, “Estudio de Condiciones Técnicas para la inyección de CO2 como Método de Recuperación Mejorada en el Campo Edén Yuturi EPF Bloque 12,” Universidad Tecnológica Equinoccial, 2016.

[52] D. Quezada and C. Vázquez, “Estudio de Simulación Matemática para la Evaluación de un Fracturamiento Hidráulico en el Campo Lobo,” Universidad Central del Ecuador, 2018.

[53] S. Vicuña, “Evaluación de la Factibilidad de Industrializar Helio a partir de Gas Natural y Gases de Pozos Petroleros Producidos en Ecuador,” Escuela Politécnica Nacional, 2011.

[54] C. Jiménez, “Optimización de los Procesos en las Facilidades de Producción en el Campo Sacha, Estación Sacha Central,” Escuela Politécnica Nacional, 2009.

[55] G. Martínez, “Estudio Técnico de la Obtención de CO2 a partir del Gas Asociado en el Campo Indillana y su Aprovechamiento para ser Utilizado en Recuperación Mejorada,” Universidad Central del Ecuador, 2017.

[56] Duane B.; Myers, “Methane Emissions from the Natural Gas Industry. Volume 14: Glycol Dehydrators,” 1995. Accessed: Aug. 17, 2021. [Online]. Available: https://www.epa.gov/sites/default/files/2016-08/documents/14_glycol.pdf.

[57] U.S. Energy Information Administration (EIA), “Henry Hub Natural Gas Spot Price ,” *Natural Gas*, Sep. 01, 2021. https://www.eia.gov/dnav/ng/hist/rngwhhdM.htm (accessed Sep. 05, 2021).

[58] C. Carrillo and R. Parra, “Comportamiento del margen de refinación en el sector hidrocarburífero del Ecuador en el 2018,” *FIGEMPA Investig. y Desarro. Univ. Cent. del Ecuador*, vol. 11, no. 1, pp. 30–39, Jul. 2021, doi: 10.29166/revfig.v11i1.2630.

[59] EP Petroecuador, “Informe Estadístico. Enero-Julio 2021,” Jul. 2021. Accessed: Sep. 26, 2021. [Online]. Available: https://www.eppetroecuador.ec/?p=3721.

[60] EP Petroecuador, “Valor del Subsidio de Combustibles,” Resolución N°3184 del SRI, 2021. Accessed: Sep. 26, 2021. [Online]. Available: https://www.eppetroecuador.ec/wp-content/plugins/download-

monitor/download.php?id=391.

[61] Agencia de Regulación y Control de Energía y Recursos Naturales no Renovables (ARC), "Precio de Combustibles," *Segmento Gas Natural*, 2021. https://www.controlrecursosyenergia.gob.ec/precios-combustibles/ (accessed Sep. 26, 2021).

[62] Agencia de Regulación y Control Hidrocarburífero (ARCH), "Precios Combustibles," *Segmento Gas Natural*, Jun. 28, 2020. https://www.controlhidrocarburos.gob.ec/precios-combustibles/ (accessed Sep. 26, 2021).

[63] EP Petroecuador, "Precio de Venta en Terminal para las Comercializadoras Calificadas y Autorizadas a Nivel Nacional," 2021. Accessed: Sep. 26, 2021. [Online]. Available: https://www.eppetroecuador.ec/?p=8062.

[64] Petroamazonas EP, "Programa de Eficiencia Energética: Aprovechamiento de Gas Asociado en el Distrito Amazónico ," 2018. Accessed: Aug. 11, 2021. [Online]. Available: https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2018/10/Estrategiaaprovechamientogasasociado.pdf.

[65] Petroamazonas EP, "Reporte Gerencial 2018," Feb. 2019. Accessed: Aug. 11, 2021. [Online]. Available: https://www.petroamazonas.gob.ec/wp-content/uploads/downloads/2019/02/Reporte_Gererencial_2018_Final-pliegos-2.pdf.

[66] Ministerio de Energía y Recursos Naturales No Renovables, "Proyecciones de la industria Hidrocarburífera. Petróleo y Gas en el Ecuador," May 2019. Accessed: Aug. 11, 2021. [Online]. Available: https://spe-ecuador.org/sites/default/files/2019-05/Presentación SPE Ministro Carlos Perex 08 de mayo.pdf.

APPENDIX

APPENDIX A:

Associated gas in the Amazon region and assumptions for the economic study

Table A.1. *Fields flowrate in the last months* [49]

Date	Flowrate [MMscfd]										
	ITT Gas	**EY Gas**	**OY Gas**	**LA Gas**	**PA Gas**	**SH Gas**	**CU Gas**	**LI Gas**	**AU Gas**	**SA Gas**	**IN Gas**
April 15th, 2021	1.81	4.65	0.96	5.96	8.24	20.27	4.66	10.12	9.36	14.55	4.26
April 20th, 2021	1.83	5.02	0.96	5.82	8.73	20.10	4.78	9.51	9.23	14.39	3.82
April 25th, 2021	1.86	4.72	0.97	5.72	9.03	19.28	4.97	9.49	9.21	13.90	4.51
April 30th, 2021	1.88	4.81	0.93	5.65	9.18	18.64	5.00	9.13	9.12	14.59	4.13
May 5th, 2021	1.86	4.86	0.93	5.64	8.49	19.95	5.12	9.31	9.12	14.68	4.16
May 10th, 2021	1.87	4.86	0.93	5.62	8.27	20.98	5.18	8.90	9.11	14.73	4.60
May 15th, 2021	1.85	4.95	0.96	5.79	8.80	20.89	5.11	8.40	9.37	14.70	4.27
May 20th, 2021	1.85	4.90	0.95	5.75	8.09	19.88	5.10	8.54	9.34	14.82	4.24
May 25th, 2021	1.89	4.68	0.96	5.74	8.29	19.19	5.03	8.49	9.40	14.78	3.88
May 30th, 2021	1.87	4.25	0.94	5.74	8.28	20.60	5.28	8.45	9.46	14.70	4.07
June 5th, 2021	1.86	4.62	0.94	5.73	8.57	20.58	5.23	8.58	9.29	14.69	3.83
June 10th, 2021	1.85	4.36	0.94	5.75	8.42	20.21	5.30	8.62	8.54	14.64	3.54
June 15th, 2021	1.85	3.98	0.95	5.75	8.40	19.90	5.41	8.56	9.12	14.64	4.10
Average	1.86	4.67	0.95	5.74	8.52	20.04	5.09	8.93	9.20	14.60	4.11
Standard deviation	0.02	0.30	0.01	0.09	0.33	0.68	0.21	0.54	0.23	0.24	0.29

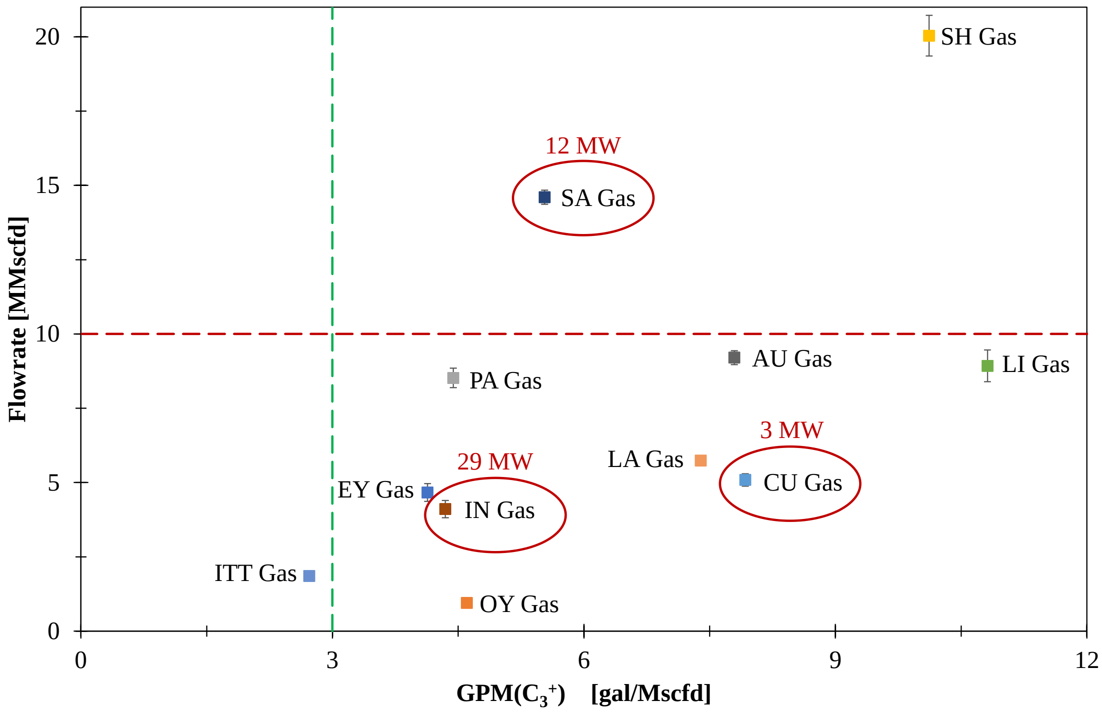

Figure A.1. *Installed capacity to produce energy through associated gas by the Optimization of Power Generation and Energy Efficiency (OGE&EE) Program* [64–66]

Table A.2. *Premises and Assumptions for the Capital Cost Data* [25,48]

Cost Include	Cost Exclude
Costs directly associated with the process	Miscellaneous equipment associated with grass-roots plant
Two-month startup operating expenses	Costs not directly associated with the process
Initial supplies and minimum spare parts	Site and site preparation
Sales taxes	Owner home office costs
Contingence of 10 %	Interest on investment during construction
New facilities only	Construction insurance and bond costs
2017 U.S. Gulf Coast location	

APPENDIX B:

Ethane and propane recovery level dependency

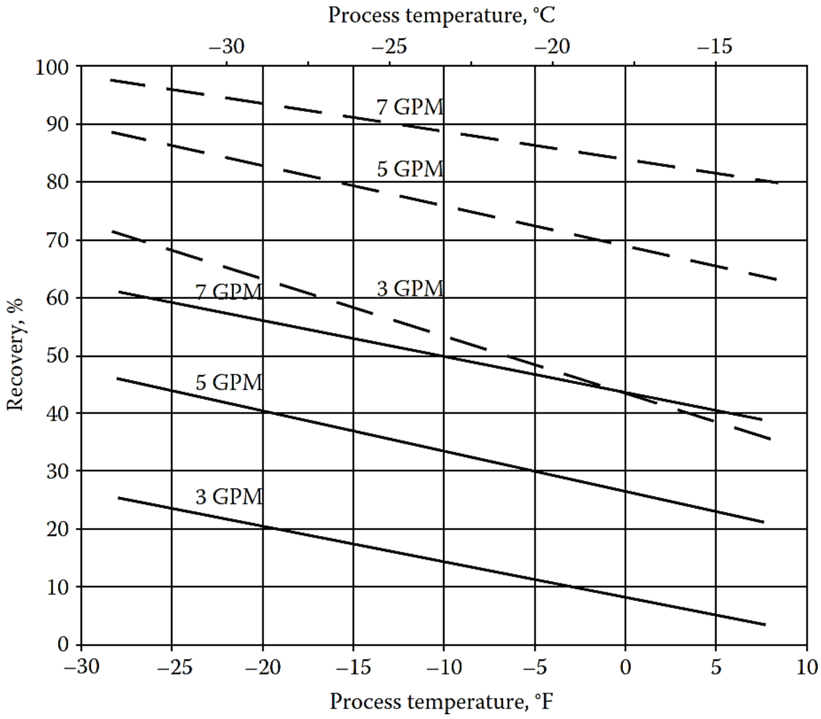

Figure B.1. *Recovery of ethane and propane as a function of the separation temperature and NGL content of feed. Operating pressure is 600 psig (41 barg) and GPM is based upon C_3^+. The solid and dashed lines represent ethane and propane recovery, respectively. Three, five, and seven GPM are equivalent to 0.4, 0.7 and 1 m^3/103 Nm^3* [25]

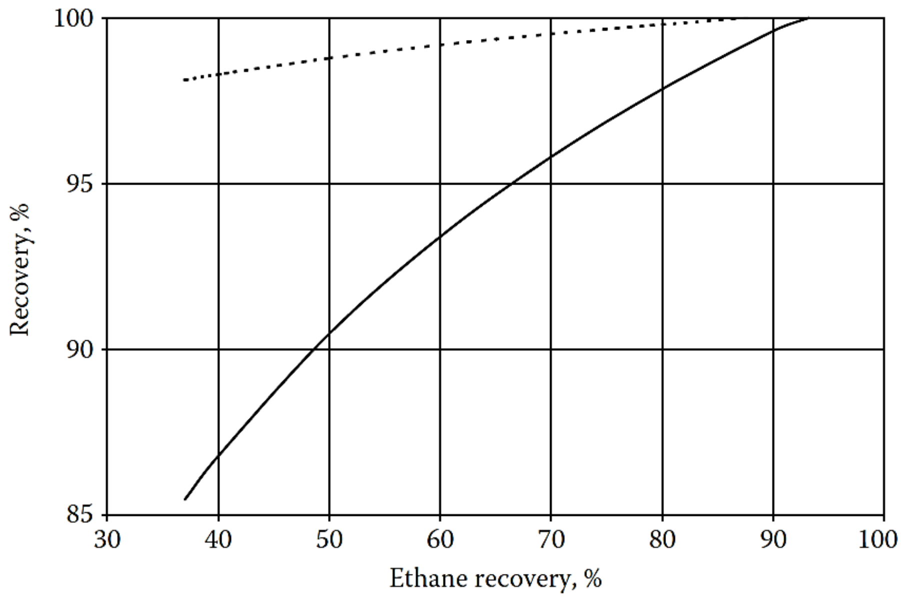

Figure B.2. *Recovery of propane and butanes as a function of ethane recovery rate. The solid and dashed lines represent propane and butanes recovery, respectively* [25]

APPENDIX C:

Economic Study Data

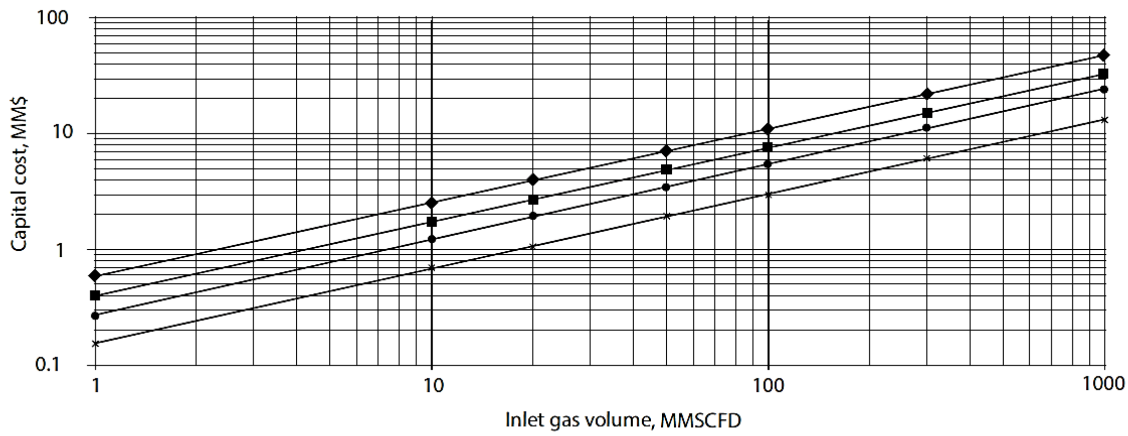

Figure C.1. *Capital cost of gas treating by use of DEA as a function of plant capacity in 2017. The lines denoted by x, ●, ■, ♦ denote 2 %, 5 %, 10 %, and 20 % acid gas removal, respectively* [25,48]

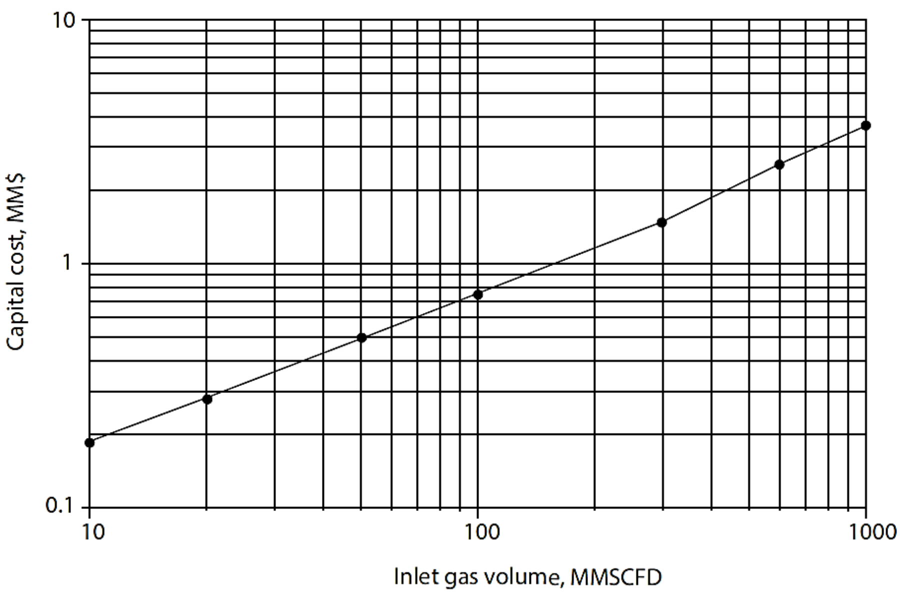

Figure C.2. *Capital cost of TEG dehydration in 2017* [25,48]

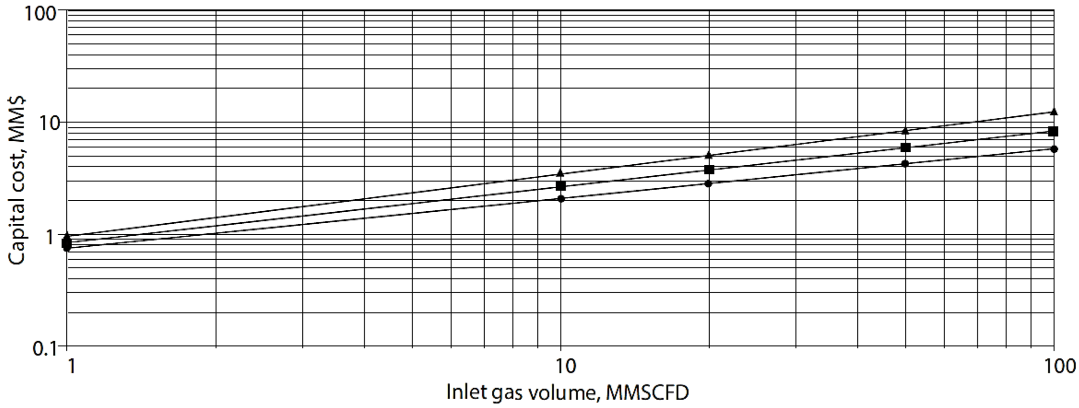

Figure C.3. *Capital cost of NGL recovery with straight refrigeration in 2017. The lines denoted by ●, ■, ▲ represent 1.5, 3, and 6 GPM (0.2, 0.4 and 0.8 m^3 liquid/1,000 m^3gas) on a C_3^+ basis, respectively* [25,48]

Table C.1. *Estimated costs for SA Gas facilities in 2021*

Infrastructure for SA Gas 2021	
Facility	**Capital Cost USD**
Gas Sweetening:	1.16 MM
Gas Dehydration:	0.29 MM
Natural gas liquids recovery:	5.78 MM
Natural gas liquid fractionation:	2.89 MM
Total cost of stages	10.11 MM
Other costs and contingency of 40 %	4.05 MM
Total estimated plant cost	14.16 MM