An Analysis Based on
Non-Parametric Methods
2008-2017

Global Oil Industry Efficiency and Productivity in the Upstream Sector

COMUNICACIÓN CIENTÍFICA

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DOI.ORG/10.52501/cc.128

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Global Oil Industry Efficiency and Productivity in the Upstream Sector : An Analysis Based on Non-Parametric Methods, 2008-2017. / Juan José Ortiz Villegas, Jorge Víctor Alcaraz Vera (autores). — Ciudad de México : Comunicación Científica, 2023.

184 pages: General index, index of tables, graphics and figures, index of abbreviations and acronyms, graphs, figures, tables, formulas, references, glossary, annex. (Colección Ciencia e Investigación)

ISBN 978-607-59874-0-8

DOI 10.52501/cc.128

1. Industria Petrolera. 2. Recursos petrolíferos. I Ortiz Villegas, José Juan, autor. II. Alcaraz Vera, Jorge Víctor, autor. III. Título. IV. Serie.

LC: TP690.5 Dewey: 338.476.655

First edition in Ediciones Comunicación Científica, 2023.

Cover Design: Francisco Zeledón • Interiors: Guillermo Huerta

Ediciones Comunicación Científica, S. A. de C. V., 2023
Av. Insurgentes Sur 1602, piso 4, suite 400
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ISBN 978-607-59874-0-8
DOI 10.52501/cc.128

Esta obra fue dictaminada mediante el sistema de pares ciegos externos.
El proceso transparentado puede consultarse, así como el libro en acceso abierto, en **https://doi.org/10.52501/cc.128**

Index

Abstract

This research determines the variables that have shown greater influence on the total factor productivity (TFP) of the world oil industry's upstream sector between 2008 and 2017. The theoretical and methodological approach behind this work is based on two non-parametric frontier methods: the Data Envelopment Analysis (DEA) and the Malmquist index. These models measure the upstream sector's technical efficiency levels, their changes, and their effects on the oil industry's TFP. The results reflect the efficient performance of Iran, Angola, Kuwait, Saudi Arabia, United Arab Emirates; these countries belong to the Organization of Petroleum Exporting Countries (OPEC). In addition, non-OPEC countries show a tendency towards greater technical efficiency and higher TFP levels. In conclusion, low technical efficiency for National Oil Companies (NOC's) is caused by low crude oil production and excessive use of labor force. For International Oil Companies (IOC's) low technical efficiency is the result of recovery deficits in proven oil reserves and the underutilization of exploration wells.

Keywords: *technical efficiency, TFP, oil industry, DEA, Malmquist index.*

Resumen

Esta investigación determina las variables que mayor influencia han mostrado en la productividad total de los factores (PTF) del sector *upstream* de la industria petrolera mundial entre 2008 y 2017. El enfoque teórico y metodológico detrás de este trabajo se basa en dos métodos fronterizos no paramétricos: el Análisis Envolvente de Datos (DEA) y el índice de Malmquist. Estos modelos miden los niveles de eficiencia técnica del sector *upstream*, sus cambios y sus efectos en la PTF de la industria petrolera. Los resultados reflejan el desempeño eficiente de Irán, Angola, Kuwait, Arabia Saudita, Emiratos Árabes Unidos; estos países pertenecen a la Organización de Países Exportadores de Petróleo (OPEP). Además, los países no pertenecientes a la OPEP muestran una tendencia hacia una mayor eficiencia técnica y mayores niveles de PTF. En conclusión, la baja eficiencia técnica de las Compañías Petroleras Nacionales (NOC) es causada por la baja producción de petróleo crudo y el uso excesivo de mano de obra. Para las compañías petroleras internacionales (IOC), la baja eficiencia técnica es el resultado de los déficits de recuperación de las reservas probadas de petróleo y la subutilización de los pozos de exploración.

Palabras clave: *eficiencia técnica, TFP, industria petrolera, DEA, índice de Malmquist.*

Introduction

The world's oil industry has played a leading role in developing economies. This is due to its strategic relevance in national incomes as well as its presence in international activities. Petroleum is still the product of choice for the world's energy supply, and its processing is crucial in the design of national projects and development plans around the world. The income it generates and the need for derivatives in the development of many industries are proof of this.

Petróleos Mexicanos (PEMEX) is the leading company in Mexico's oil industry; some structural changes have recently been implemented in its internal organization. Its role as a National Oil Company (NOC) has defined the competition in domestic and international markets.

The oil sector is currently going through a time of crisis in all hydrocarbon-producing countries due to irreversible changes in extraction projects and to unequal procurement. This is now challenging the global oil industry, and the consequence is a fall in the price of crude oil (Coronado & Noño, 2016).

In addition to the global oil crisis, Lajous (2014), mentions that Mexico's oil industry is facing a critical turning point because the expansionary phase of the crude oil production cycle that started in 1996 has already ended for Mexico.

There are national and international pressures to develop a sustainable economy that guarantees energy security, economic growth, and environmental care (Bhattacharya *et al.,* 2016; Scholten and Bosman, 2016). Despite fossil fuel pressures and increasing oil price volatility (Drollas *et al.*, 2012; Salameh, 2014; Welch, 2019), fossil energies will remain the basis for global economic development. However, renewable sources are expected to become more relevant during the following decades; they will become an essential element for humanity's development and welfare in the future (International Energy Agency, 2014, 2015; Bhattacharya *et al.,* 2016).

The world's energy supply is still dominated by non-renewable fossil fuels; in 2018, 38% of it was generated by coal, 23% by natural gas, and only 3.3% by petroleum (IEA, 2020). Petroleum has been on a downward trend as a fuel for electricity generation since 1980, while renewables and nuclear power continue to increase their share.

On the other hand, petroleum is the main input for fuels in the transport industry; it represents 92.3% of it, and 33.9% of the industrial sector (IEA, 2020). A fact to consider is that, as of 2018, 88% of natural gas has been obtained from fields in which petroleum is also extracted (API, 2018).

Energy transition aims at reducing CO_2 and greenhouse gas emissions. This is essential to reverse the effects of human activity on the environment and reduce global temperature (UN, 2015). The International Energy Agency presented several scenarios and mitigation strategies by country to limit temperature increase to 2 °C by 2050. Some recommendations are enhancing the procurement and application of renewable energy and reducing fossil fuels consumption. The participation of such fuels at a 50% is suggested even in this scenario (International Energy Agency, 2009).

Economic growth generates an increase in energy consumption. For this reason, the consumption of fuels derived from petroleum and natural gas will continue to be present in future energy generation projects. The need for inputs in the petrochemical, pharmaceutical, and petroleum-derived manufacture industries must also be considered. In addition, there are no viable products to replace the requirements for fossil fuels on a large scale in the industrial, metallurgical, transportation, and aeronautical sectors (González-López & Giampietro, 2018).

This research shows the need to maintain oil production in the world even when the demand has been gradually reduced. It is necessary for participating countries and organizations to use their resources efficiently and achieve the greatest benefit possible. It will also be essential for those companies in charge of oil exploration and extraction to use the best technology available and thus become a reference for oil supply in the market. They should also maintain and improve efficiency levels to obtain the highest productivity of the factors used in production.

This research analyzes the management of the oil industry's upstream[1] sector in the main oil producing countries. Emphasis is placed on Mexico's performance in the upstream sector through PEMEX's subsidiary company Exploración y Producción (EP) from 2008 to 2017, prior to opening oilfield exploitation to domestic and foreign private companies. A comparison is made among fifteen countries to identify the effect that technological shift and technical efficiency had on TFP[2] changes, identifying the best performing nations in each period and using them as a reference to evaluate the rest.

It is clearly important to evaluate the changes that have affected the productivity of PEMEX in the upstream industrial sector. It is also necessary to identify factor productivity and the effects that technological change and technical efficiency have on such changes. The industrial sector in general as well as each Decision-Making Unit (DMU)[3] will be evaluated; this corresponds to the results of the oil industry's *upstream* sector in each of the countries selected for this research.

This research used the non-parametric approach of DEA to analyze the performance of the 15 main oil producing countries in physical units, thus determining the technical efficiency levels of each one based on the models proposed by Banker *et al.* (1984) and Lo *et al.* (2001), in which variable returns to scale are considered. DEA also provides a slacks-based analysis to determine the causes of distancing from the efficient frontier of those countries that present inefficiency and did not reach product maximization.

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[1] The upstream oil industry also refers to exploration and exploitation; it involves underground, shallow water, and deep-water search for natural gas and oil reservoirs as well as drilling and exploitation of reservoirs to obtain crude oil and gas.

[2] Total Factor Productivity (TFP) is the ratio of net output to the sum of factor inputs such as labor, capital, and technical efficiency (Comin, 2010).

[3] Units under study in Data Envelopment Analysis. A DMU is usually considered responsible for converting inputs into outputs, and its performance is evaluated (Cooper *et al.,* 2007).

Additionally, benchmarking is used to determine which countries were referents of efficient behavior in each period.

The Malmquist index is applied to define changes in efficiency and technology. This methodology is a dynamic analysis of the efficient frontiers obtained through DEA. The evolution of each country was evaluated from one period to the next and how these changes affected the total productivity of the production factors employed.

Chapter I describes PEMEX context; it provides a historical perspective and the structural changes of the company since the effects of the energy reform began, the reason, and the moment in which its subsidiary firm, EP, arises along with the other subsidiaries. The chapter elaborates on capital investment and operating expense fluctuations, as well as the changes the company has faced in international trade after price and oil reserves variations. Thus, the issue of how the upstream sector of Mexico's oil industry has been performing is raised. The focus is on the importance of measuring its technical efficiency, identifying technological changes, and assessing the impact on factor productivity variations compared to other countries participating in the same sector of the industry.

Chapter II describes the oil industry as a whole and its international activity. It provides an inductive approach on the role of Mexico's industry in the world as well as the role of EP in the sector.

Chapter III recounts those theories addressing concepts, typology, estimation methods, scopes, and discussions on productivity and efficiency. Based on the research questions, goals, hypothesis, limitations, and scopes, a theoretical framework is presented and directed according to Farrell and his typology of efficiency, the different notions of productivity, the different concepts of TFP, and the role of technological change. Estimations of capital, labor, and the effect of efficiency on productivity are provided, as well as the efficiency types and the possibility of including variable returns to scale in the production function. The analysis is made from an envelope production function.

The increasing need for financial resources and production inputs puts greater pressure on institutions to make a more efficient use of their available resources. PEMEX remained in the market as a recognized brand with high profitability indicators until 2017 (PEMEX, 2018) when financing dropped and productive assets from previous periods had to be used. The main goal of this research is to determine the role of technical efficiency and technological change in productivity results and detect if these results are due to changes in capital and labor structures[4] or due to the efficiency achieved by managerial agents.

Chapter IV details the methodological proposal of this research. It is based on non-parametric deterministic frontier models, which allow to pinpoint the efficiency measures of those countries under study as well as Mexico's role in different periods. A slacks-based analysis is also performed to identify how the combination of inputs obtained a certain number of outputs and how far were those inefficient units from achieving better efficiency levels. The whole DEA process involves a *benchmarking* analysis[5]. It is used to compare all countries with those with better performance and to detect the countries that were referents when determining the envelope frontier.

In this same chapter, we describe the Malmquist index method used to calculate TFP; this helps to distinguish the influence of technical efficiency and technological change on productivity changes. The selected techniques are compatible since they are deterministic and radially measure changes on the three variables through the selected periods.

Chapter V consists of the results obtained from applying the methodology previously described. The results show the pure technical efficiency (PTE), scale efficiency (SE), overall technical efficiency (OTE), slacks-based analysis, benchmarking based on DEA, and changes in OTE, technological change (TC), and TFP through the Malmquist index.

Chapter VI provides the conclusions of this research by enumerating the possible causes of the results obtained in the OTE, PTE and SE scores. It describes the changes occurred in the period under study, the PTE, technological change, and how these variables impacted on TFP.

Chapter VI also gives recommendations based on the conclusions. The focus is on the upstream sector of the main oil producing countries for the specific conditions of OPEC and non-OPEC member countries, the

[4] The productive factors mostly represented in productivity functions are capital and labor.

[5] It is the process of comparing a group in which each element is compared to the one or ones with the best results.

American countries, and Mexico in particular. Finally, some considerations for future lines of research and the application of other methodological tools are given along with some implications of the current changes that impose new challenges and variables to analyze. Such changes are the transition to renewable energies, the current oil crisis, and the future of this industry.

I. Research Fundamentals

This chapter describes the situation of PEMEX in Mexico, the effects of the energy reform on its operations, and how these changes affect its performance at the national and international levels. The research problem, questions, objectives, and hypotheses are then exposed to explain how efficiency and technological change affected the upstream sector's productivity of the global oil industry as well as the results obtained by this sector in Mexico through the management of PEMEX EP.

PEMEX's National and International Context

Intensive exploitation of hydrocarbons in Mexico began in 1904. Early in the 20th century, the operation of companies mainly from England and the United States (U.S.) made Mexico the second largest oil supplying nation in the world by 1920. In 1938, President Lázaro Cárdenas expropriated all assets of foreign oil companies operating in Mexico at the time; this action prompted constant threats by those foreign companies to withdraw their capital if the government forced them to sign the agreement with the oil workers trade union "Sindicato de Trabajadores del Petróleo de México", which demanded fair labor conditions for the employees of these companies among other issues.

The government's main argument was that petroleum was a source of energy that belonged to all Mexicans. Therefore, only governmental entities should exploit the resources of the oilfields with the sole purpose of benefiting the nation (De la Fuente, 2013). However, PEMEX continued to hire the services of some U.S. companies until 1958 when Article 27 of the Constitution came into force, which definitively prevented such practices (Ribando *et al.,* 2015).

During the 1980's, PEMEX consolidated its position as one of the main contributors to Mexico's public finances, contributing nearly 30% of the Federal Government's income (Colmenares, 2008). This was achieved mainly due to the discovery of Cantarell field in 1979. It was the third largest reserve in the world at the time, only behind Ghawar and Burgan fields in Saudi Arabia and Kuwait, respectively. This discovery was accompanied by promises about job openings, technological development, commitment to industrialization, and infrastructure. President López Portillo insisted on taking advantage of such wealth and reinvesting it to guarantee Mexico's future "beyond the petroleum". However, it took Cantarell 24 years to reach its peak production (Romo, 2015).

From 1980 onwards, the first signs of PEMEX privatization appeared; the state-owned company began to allow private companies to invest only in some areas. This process formally began in 1986 when petrochemicals were reclassified into primary and secondary, and PEMEX only kept exclusivity over the former. In 1992, PEMEX was divided into four subsidiaries that would compete against each other to improve efficiency. Each subsidiary was created with its own personality and assets: *PEMEX Exploration and Production, PEMEX Refinery, PEMEX Gas and Petrochemical*, and *PEMEX Petrochemical*. This division was intended to allow subsidiaries to compete against each other to produce and sell products at international prices. These companies are administratively dependent on PEMEX, but their operation is independent. This situation led to years of inefficiency and lack of capital (Reyes Hernández *et al.,* 2014).

By 1995, these subsidiaries were no longer considered of strategic value to the government, and private capital was allowed to participate in the production, transportation, storage, distribution, and sale of natural gas. During the same year, the "Productive Infrastructure Investment Project with Deferred Registration in Public Spending" (PIDIREGAS) was created as a financial mechanism that allowed the private sector to control investments in PEMEX. It became the main source of financing for the state-owned company. By 2005, 90% of investments in PEMEX came from PIDIGERAS (Bartlett Díaz *et al.,* 2018).

In 2002, multiple contracts were carried out for services required by PEMEX; this mechanism allowed PEMEX to hire private companies, mainly foreign, for the search and production of gas.

In 2004, Mexico had reached its highest level of petroleum extraction from oilfields; since then, it has been on a downward trend. Mexico's total oil production has declined 27% since 2004. In 2014, an average of 2.8 million barrels per day of petroleum and other liquids were produced. Crude oil accounts for 2.4 million barrels, or 87% of total production, while the remaining settlements correspond to liquid gas and refined products. Crude oil production in 2014 was notoriously the lowest level since 1986, and it remained down until a slight rebound in 2017; this was due to the precarious recovery in international oil prices. The US became an oil exporter to Mexico during 2015, something that had not happened for more than 20 years (Castro *et al.,* 2017).

In 2014, the Mexican government passed an energy reform allowing private companies to freely participate in the energy sector market. This had previously been prohibited for eight decades. The reform is expected to significantly change the structure of the energy sector and accelerate the diversification of energy production. Moreover, changes in the energy sector and production can lead to structural changes in the rest of the economy and ultimately generate significant economic benefits for the country (SENER, 2014).

However, the fundamental role of the energy sector in oil production makes it difficult to determine the possible effects of the reform. The new structure (change from state control to competition with private parties), implied the creation of regulatory agents by the reform. Such regulation will also significantly affect the characteristics of production, investment, competition, and control of activities in the energy sector and all other affected economic sectors (Castro *et al.,* 2017).

PEMEX was divided into six Subsidiary Productive Companies (SPC) in 2015: Exploration and Production, Perforation and Services, Industrial Transformation, Ethylene, Fertilizers, and Logistics Industrial Cogeneration, to establish a structure and a basic organization according to the basic functions of the different areas that make up PEMEX (PEMEX, 2018).

- *PEMEX Exploration and Production (EP).* Exploration and extraction of petroleum and solid, liquid, or gaseous hydrogen carbides in the national territory, in the country's exclusive economic zone and abroad.
- *PEMEX Perforation and Services (PPS).* Drilling, completion, restitution, and execution services to wells in onshore and offshore fields. PPS also offers other services to wells such as cementing, logging, coiled tubing, among others.
- *PEMEX Industrial Transformation (PTRI).* Refining, transformation, processing, importing, exporting, commercialization, retailing, and sale of hydrocarbons, petroleum products, natural gas, and petrochemicals.
- *PEMEX Logistics (PLOG).* Transportation and storage services for hydrocarbons, petroleum products, petrochemicals, and other related services to Pemex, Subsidiary Productive Companies, and third parties through transportation strategies by pipeline and by maritime and land means, as well as the sale of storage and handling capacity.
- *PEMEX Ethylene (PE).* Production, distribution, and commercialization of methane, ethane, and propylene derivatives on its own or on behalf of third parties.
- *PEMEX Fertilizers (PF).* Production, distribution, and marketing of ammonia, fertilizers, and their derivatives, as well as the provision of services related to these products.

At the end of 2017, the corporate structure consisted of six directorates: Planning, Coordination and Performance; Information Technologies; Alliances and New Businesses; Finance; Administration and Services; and Legal; thus, PEMEX's management structure is depicted in Figure 1. On the other hand, according to its 2017 annual report, the total number of occupied positions in Pemex stood at 124 660, which represented a decrease of 1.5% with respect to the close of 2016 (PEMEX, 2018).

Effects of the Energy Reform

The energy reform could have a large effect on the economy, both positive and negative, as Mexico is an oil country that currently ranks seventeenth in oil reserves. Its economy is heavily dependent on crude oil exports, which accounts for 15% of its total exports and covers about 37% of government revenues. The government expects the reform to accelerate production, attract new technologies and capital, and enable unconventional exploitation (fracking[1]) of oil and gas reserve deposits (Guevara *et al.,* 2017). However, there is a potential negative effect of the reform reducing oil-related government revenues and converting them into public spending if revenues are directed to the private sector.

Although Mexico is considered a country whose economy is heavily dependent on oil, it does not have the industrial capacity to generate its own demand for oil derivatives and must import them. This situation causes the prices of these products, both for the industry and for final consumers, to be relatively higher compared to the U.S. In this respect, the government expects that greater investment by private companies will stimulate the creation of new refineries and eventually reduce prices (Guevara *et al.,* 2017). Price control will be coordinated by the Ministry of Energy (SENER) and subject to maximum allowable prices. This condition reduces the possibility for prices to fall significantly in the short or medium term. However, this has been an argument constantly used by the government to mitigate social pressure in the face of the reform. There is already a precedent in electricity rates, which suffered the effects of privatization before the oil industry did since the signing of the North American Free Trade Agreement (NAFTA) in 1994.

However, PEMEX has focused heavily on increasing the volume of production, rather than on diversifying its products or improving its processes. The main change brought by the energy reform lies in the possibility for private companies to participate in the extraction of resources from oilfields in Mexican national territory. This allows them to obtain profits, either by

[1] Fracking refers to the creation of fractures in the subsoil with pressurized water, with the aim of facilitating the extraction of hydrocarbons; it is also known as hydraulic fracturing (King, 2012).

product or in a combined fashion. This will increase production (no longer necessarily of PEMEX) and the number of proven reserves.

Mexico's dependence on imports of petrochemical products is another factor to consider. In terms of national refineries, PEMEX currently covers only 50% of the national demand for gasoline and 60% for natural gas. Virtually all petrochemicals produced domestically come from the Santa Cruz refinery, which is working at only 20% of its installed capacity (González-López & Giampietro, 2017). The modernization of existing refineries, the creation of new refineries, and the benefits they could bring have been widely discussed so that they are also a focus of attention when diversifying investments.

The work of Schulz *et al.* (2015), provides a perspective in favor of energy reform as long as it achieves the development of renewable energy[2], increased energy exports (oil, gas, oil derivatives and electricity), poverty reduction through job creation, and increased productivity reflected in the Gross Domestic Product (GDP). All these aspects should be induced by maximizing the benefits obtained from oil and by liberating the energy market, with a government capable of controlling and balancing conflicts of interest as well as compensating negative externalities. An efficient business model is determinant for the success of the reform, as is the transparent management of PEMEX and those government agencies that control and regulate the new conditions imposed.

There are also theoretical contributions that criticize the energy reform; they expect more losses than benefits in its implementation. These contributions can be summarized in five main areas:

1. The energy sector has very complex market regulations, and the current modifications do not reflect potential conflicts in the operation between private companies and PEMEX, which may lead to a depletion of existing oil reserves.
2. During the process of authorizing the reform, there were several irregularities, and a lack of transparency was evident. Also, there has never been a specific plan regarding the role that PEMEX will play;

[2] Renewable energy sources are those that, after being used, can be naturally or artificially regenerated. Some of these renewable sources are subject to cycles that remain constant in nature (Casas *et al.,* 2008).

it is not specified if it is projected as a competitive company in the private sector.

3. After the implementation of similar reforms in other countries such as Brazil, it became evident that changes were aimed at transferring wealth abroad.
4. The reform may have repercussions in the economic structure such as the separation of the energy sector from the rest of the country's economic activity, and the decline of energy companies unable to compete.
5. Companies will now face greater uncertainty regarding international energy prices. This is strongly related to the availability and prices of oil, which increases the risk in their operations and decreases their profits (Guevara *et al.,* 2017).

Given the new market characteristics, the new legislation (Art. 27 Constitutional), the identity of companies, and the regulation of operational activities, new challenges and new opportunities arise. It is essential to evaluate all agents involved. The conditions in which each agent will contribute to favor economic development are strongly linked to the productivity they have achieved. The effectiveness and efficiency of their processes stand out in addition to goal management, which is necessary to reduce the reform's negative effects; competition must lead to the improvement of the nation's general welfare in both its industry and its people.

Research Problem

There are multiple variables that affected the change in PEMEX EP productive performance. There are latent conditions that limit access to capital and labor inputs for the upstream sector of Mexico's oil industry. There are also important structural changes in which the Mexican and global oil industry is immersed; barriers are being eliminated between private and national companies to cooperate and access new technologies.

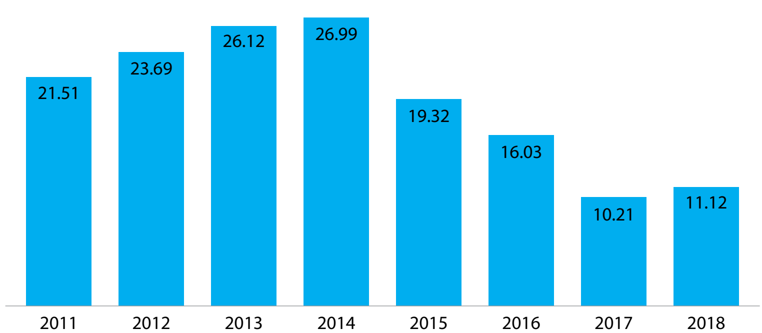
Each country has been affected in different ways over time by these kinds of events, by changes in the world market, and within each of their domestic markets. The productivity and efficiency changes experienced by each nation are the reason for this research to analyze and specify the main variables that impacted the TFP of the main oil producing countries between 2008 and 2017.

Investment in PEMEX

One of the main problems facing the oil industry is the depletion of petroleum and gas deposits. This is due to the lack of incorporation of reserves and the stagnation in processing refined products and generating petrochemical products. All this is caused by the lack of investment due to the country's economic crises, by crude oil price volatility[3], and by the recent changes in the flow of international trade. Thus, it is necessary to foster financial resources allowing capital formation, technology acquisition, and the recruitment of trained human resources.

Graph 1. *Capital Expenditures (CAPEX)*

Millions of dollars



Source: PEMEX (2018).

Faced with the lack of fiscal resources in the 1990's, the government adopted a financing scheme that allowed the participation of foreign capital to boost the oil industry. This scheme was named PIDIREGAS, and it initially served to obtain financial resources after the scarcity of public funds.

3 Changes in crude oil prices respond quickly in the stock markets compared to other commodities, and the effect is reciprocal with other sectors.

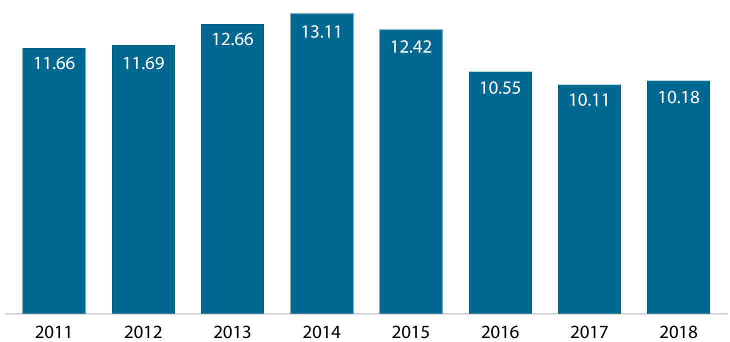
In 2017, 90% of the investment in PEMEX was obtained through PIDIREGAS (PEMEX, 2017).

In just four years, government decisions imposed two structural changes on the oil industry: the energy reform and the new division of its EPS. Then came a crisis in production, world demand, and prices of the PEMEX products. Considering this, SPC management of capital assets and their workforce should be evaluated in terms of their benefit-cost ratio to determine if investment is distributed adequately and to identify those companies that are inefficient in their behavior.

The investment flow has remained downward since 2011 with only a slight rebound in early 2018 in terms of capital expenditures (CAPEX[4]). However, it is still below 50% of all investment acquired in 2014. Investment in operating expenses (OPEX[5]) is perceived stable during this period but without the level of investment of previous years. This means that PEMEX has not recently increased its productive facilities; it only maintained and remodeled its old infrastructure.

Graph 2. *Operating Expenditure (OPEX)*

Millions of dollars



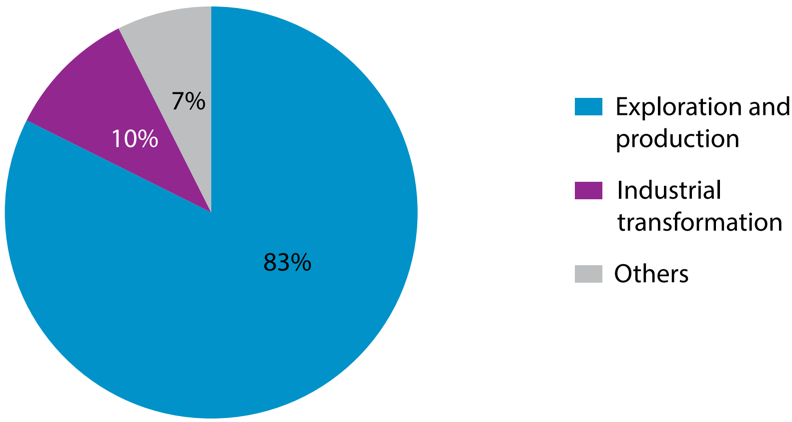
Source: PEMEX (2018).

[4] Abbreviation for Capital Expenditures, which indicates the amount of money spent on capital goods of a given company.

[5] Abbreviation for Operating Expense, which is the capital used to maintain or improve a company's tangible assets.

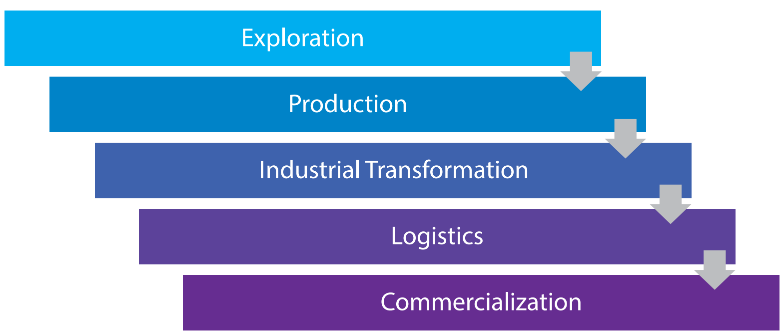
The investment made by PEMEX and its subsidiaries must be authorized by PEMEX's annual budget. It is approved by Mexico's Congress, and most of it is assigned to PEMEX EP. An average of 80% of the budget is allocated to this subsidiary.

Graph 3. *Investment by SPC-PEMEX 2018*



Note: "Others" includes the following SPC: Fertilizers, Ethylene, Cogeneration, Drilling, Logistics.
Source: Author's design based on PEMEX (2018).

Figure 1. *PEMEX Value Chain*



Source: Authors' design based on PEMEX (2018).

PEMEX EP is the subsidiary receiving the largest investment; it is a backbone in PEMEX's value chain, and it has the largest production. It is also PEMEX's main income source and has the largest number of assets.

Efficiency in the use of resources is essential for the supply and operation of the remaining SPC and holds a leading role in the oil industry and the energy sector.

PEMEX International Trade

Revenues from international trade represent PEMEX's main income source and a justification for financing exploration, production, refinery, logistics, and distribution projects. The authorized budget distributed among all SPC is calculated on the production achieved. Ever since its expropriation, PEMEX had kept a growing performance in its production and foreign market participation. This situation reached its peak after the discovery and exploitation of Cantarell field. This trend was also favored by a relative stability in international oil prices, which allowed PEMEX a not so volatile allocation. However, there was a constant price fall from 2007 to 2016, when an agreement was signed between OPEC and 11 non-OPEC countries to limit the global supply of crude oil. This resulted in an increase in international crude oil prices.

The following graphs show the results both in volume and international trade value for PEMEX EP. They display the existing trend since the creation of the subsidiary until now and the imports of the rest of the SPC.

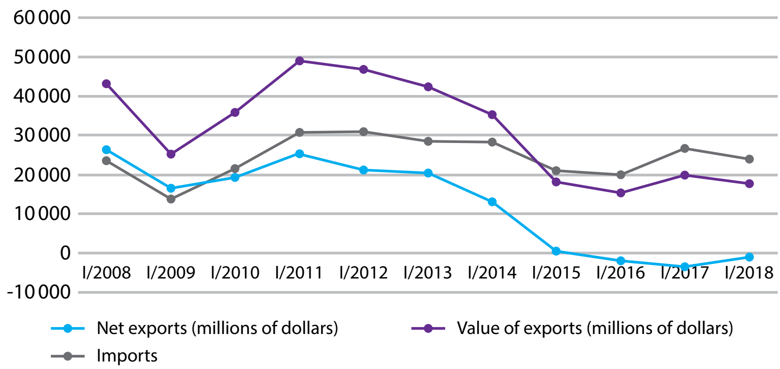
Graph 6 highlights the crisis resulting from the depletion of reserves in Cantarell field in 2009. However, there was a clear recovery and record exports in 2011. From this point on, there was a shift in trend attributed to the supply increase made by OPEC[6] countries. This trend showed a slight rebound through 2016 when the supply agreement was signed to stabilize market prices again. However, the level reached in 2017 is barely the same as in 2004 (PEMEX, 2017).

Imports show a correlation with exports, but a stabilization was appreciated after 2011, and the perceptions achieved by exports were exceeded by 2015. This makes it clear that the value and the need for imports increased, that oil and petrochemical products have a higher added value, and that the assets of other subsidiaries are not being used to meet this demand.

[6] As per the executive summary on pages 4-5 of PEMEX's 2017 annual report.

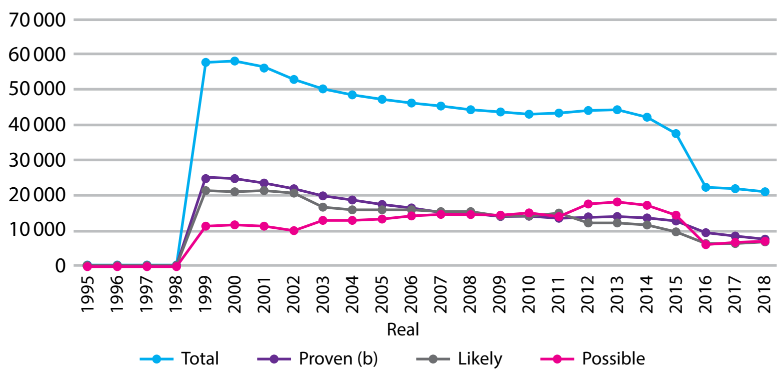
Therefore, net exports presented negative value from 2015 to 2017 and can be expected to be the same for 2018.

Graph 4. *PEMEX International Trade*



Notes: Data are presented in millions of dollars. Imports correspond to natural gas, petroleum products, and petrochemical products.
Source: Author's own design based on data from SENER (2014) and PEMEX (2018).

Graph 5. *PEMEX Hydrocarbon Reserves*



Notes: For the estimation of proved reserves, the US Securities and Exchange Commission (SEC) definitions have been used since 2003, and figures for previous years have also been adjusted.
Source: Author's own design based on data from SENER (2014) and PEMEX (2018).

The evolution of hydrocarbon reserves shows how little has been done to maintain the total volume of reserves since the exploitation of Cantarell in 1998. Therefore, there has been a downward trend, which was aggravated in 2015. There was also an abrupt fall after 2015 regarding proven reserves that can be exploited in the shorter term. The subsidiary will not likely manage to increase this indicator significantly in the medium term.

Problem Statement

EP is strategically important due to the amount of investment assigned to it and the priority of its products for PEMEX's value chain to cover national and international demands. EP is presented as the most relevant component of this research due to the volume of its operations and the income it represents to amortize and pay investments not only for itself, but for the rest of the subsidiaries. EP was selected to evaluate its efficiency, technological change, and TFP. This is due to the critical role that oil revenues play in public spending and because it is the subsidiary with the largest number of operating assets.

Technical efficiency, technological change, and productivity of the upstream sector including PEMEX EP will be evaluated from 2008 to 2017 in comparison with the world's main oil producing countries. This will help identify changes in the productivity of all countries, which are benchmarks of productive efficiency, technological change, and TFP over time. The trend of Mexico's oil industry in the international market will also be identified.

The decrease in investment, oil reserves, production (considering that the rebound is still below the levels of previous years), and exports, gave this research focus on PEMEX EP's management. It should be oriented to cost reduction, resource use optimization, and the optimization of production results to meet domestic, national, and international demands.

PEMEX's goals and strategy are set out in its 2017-2021 Business Plan and based on its 2017 annual report. This strategy was centered on profitability as its guiding principle, and it established the short and medium-term measures to capitalize on the historic opportunity of the Energy Reform. It provided the necessary instruments and flexibility to:

- Focus the business on strategic activities.
- Establish alliances and partnerships.
- Strengthen operational efficiency and effectiveness.

Improved processes, increased productivity and efficiency, consistent resource management, implementation of financial strategies, and solid allocation schemes would lead to achieve the goals set out in its Business Plan.

The resource constraints experienced by PEMEX EP require an analysis of both productivity and efficiency in its production processes. This will illustrate the evolution in each period from the creation of the SPC until 2017. No study with these characteristics had been carried out for PEMEX EP with the current methodological tools and comparing the main oil producing countries.

Research Questions

The adequate framing of research questions in a scientific investigation requires to specify implicitly or explicitly the dependent and independent variables, time, and space. Thus, the answers will be well oriented and will congruently solve the questions according to the results obtained.

The following research questions are posed for the analysis of the problems faced by EP.

General Questions

- Which variables had the greatest influence on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017?
- Which variables had the greatest influence on the TFP of the upstream sector in the main oil producing countries between 2008 and 2017?

Specific Questions

- What was the impact of pure technical efficiency on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017?

- What was the effect of scale efficiency on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017?
- What was the impact of technological change on the TFP of the upstream sector in the main oil producing countries between 2008 and 2017?
- What was the effect of the change in pure technical efficiency on the TFP of the upstream sector in the main oil producing countries between 2008 and 2017?

Research Goals

This work seeks the solution of the problems defined above, so the following goals are proposed. They are oriented to achieve useful knowledge generation following the scientific method, considering the limitations in data collection, the selected methodology, the type of results, and the ability of interpretation.

General Goals

- To identify the variables with the greatest influence on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017.
- To identify the variables with the greatest influence on the TFP of the upstream sector in the main oil producing countries between 2008 and 2017.

Specific Goals

- To define the impact of pure technical efficiency on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017.
- To assess the effect of scale efficiency on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017.

- To determine the impact of technological change on the TFP of the upstream sector in the main oil producing countries between 2008 and 2017.
- To explain the effect of the change in pure technical efficiency on the TFP of the upstream sector in the main oil producing countries between 2008 and 2017.

Research Hypothesis

All hypotheses constitute a judgment or proposition, an affirmation, or a negation of something. However, they are judgments of a special nature because they are provisional and exploratory propositions, and their veracity or falsity depend critically on empirical evidence. In this sense, the repeatability of results is fundamental to confirm a hypothesis as a solution to a problem (Hernández *et al.,* 2006). Hypotheses arise from a starting point, integrate the researcher's intuition with a current paradigm of the research problem, question reality, and are finally tested against reality to produce new scientific knowledge. The hypotheses proposed for this research are the following:

General Hypothesis

- Pure technical efficiency and scale efficiency were the variables with the greatest influence on the overall technical efficiency (OTE) of the upstream sector in the world's oil industry between 2008 and 2017.
- Changes in pure technical efficiency and technological change were the variables with the greatest influence on the TFP of the upstream sector in the world's oil industry between 2008 and 2017.

Specific Hypothesis

- The impact of pure technical efficiency on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017 is positive.

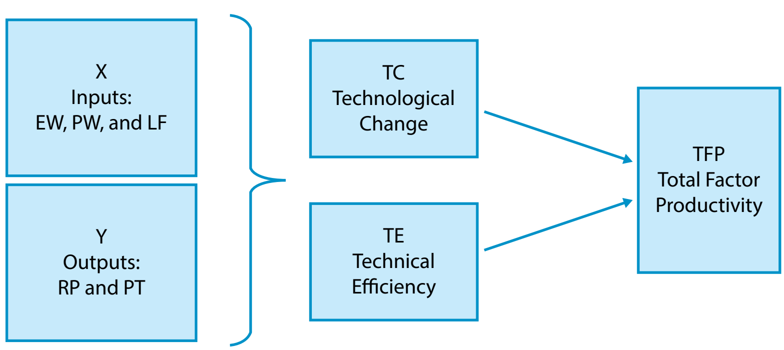
- The effect of scale efficiency on the overall technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017 is positive.
- The impact of technological change on pure technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017 is positive but smaller than the effect of changes in pure technical efficiency.
- The effect of changes in pure technical efficiency on pure technical efficiency of the upstream sector in the main oil producing countries between 2008 and 2017 is positive and greater than that of technological change.

Table 1. *Description of Variables*

INPUTS	Independent variables	Dependent variables
Active Production Wells (PW)	Scale Efficiency (SE)	Global Technical Efficiency (GTE) Actual Distance Index in Relation to Benchmark
Active Exploration Wells (EW)		
Number of Workers (LF)	Pure Technical Efficiency (PTE)	
OUTPUTS		
Proven Oil Reserves (RP)	Technological Change	Total Factor Productivity (PTF) Rate of Change in output Productivity between the set of inputs
Total Annual Production of Barrels of Oil (PT)		

Source: Author's own design (2019).

Figure 2. *Diagram of Relationships between Variables*



Source: Author's own design (2019).

Justification

This study will support PEMEX operations as it will provide a tool to evaluate the role of efficiency and technological change in the productivity of the factors used. This can help to constantly improve their processes and identify when productivity is reduced in order to react in time, formulate more realistic goals, and determine the factors that contribute to improve it. The research seeks to raise in advance the importance and strengthening of these factors and achieve a comprehensive operational development. This is especially important due to a paradigm shift in the market as the company will now compete against private enterprises including multinational companies with a strong presence in the international market.

This study can also support those agents dedicated to regulating the operations of the oil industry. Knowing the sector's behavior and efficiency throughout the period under study, the interests of both individuals, PEMEX, and all Mexican citizens can be objectively protected. The energy industry and its petroleum branch are crucial for the overall development of the country's economy. Any policy established in the future must provide a detailed analysis of the current situation to ensure the desired effects of such policies. Thus, decision makers, both governmental and private companies, can operate in a fair and well-regulated market.

Those companies that decide to enter and compete in the Mexican market must carry out a detailed study on the country's existing conditions. This work will provide a scientifically based analysis that will serve as a guide for those companies to make decisions during their entry and operational evolution in Mexican territory. In addition, it can lay the foundation for a self-analysis of their own efficiency both in Mexico and in other countries where they operate. Thus, they can make their operations efficient through *benchmarking* processes and obtain investment returns with the best benefits at the lowest costs.

This work considers the impact on all actors of the petroleum sector (industries, services and citizens). These actors are the backbone of any commercial operation, whereas evaluating the efficiency and productivity of this commodity will always be aimed at obtaining the greatest benefits without affecting other sectors. Social costs are a difficult externality to measure in any economic model. However, they must be considered since the social effects of the oil industry are strongly linked to Mexico's economic growth and to the welfare of its entire population.

The analysis of the industry in this research seeks to establish conclusions and recommendations that will benefit society. Actions will be pointed out so that the social costs do not exceed the economic benefits obtained by the industry. If so, the future activities of the industry will most likely be hindered by discontent consumers and even reduce the possibility for private companies or PEMEX to compete. Therefore, a constant study of the oil sector's operations and a continuous effort to improve efficiency provides sufficient and objective information to make decisions.

This research is longitudinal in nature[7]; it analyzes data across the 2008-2017 period to make inferences regarding changes in efficiency and TFP of the upstream or EP sector operations. This allows to detect any existing trend and to determine which factors have had any impact.

The countries with greater participation in the upstream sector of the global oil industry were considered, and the results of Mexico's PEMEX EP were included. The operations considered in this sector are exploring and discovering petroleum reserves in new deposits; updating information and assigning production estimates; developing a failure-success risk analysis; and budgeting the needs for all projects. Other operations include the extraction of crude oil, heavy gas, and standard gas; waste handling; procurement for the domestic demand; national and international distribution; the use of investment funds acquired for extraction and exploitation assets for both onshore and in-water deposits (PEMEX, 2018).

Management evaluation includes all inputs needed to generate exploration and production capital, new employees, petroleum reserves, and crude oil production.

All information needed to carry out this research is available. PEMEX, as a state-owned company, has the legal obligation to make transparent, record, and share all data related to its operations. There is also a wide theoretical and bibliographic content regarding the energy sector, specifically

[7] Analysis of a period.

the oil industry; this includes both studies on its history and operations and scientific papers on several problems relevant to this industry. As for the information related to other producing countries, it is available in their national registries, annual reports from different companies, and scientific papers.

There is also a full bibliographic collection on theories and methodologies to back up the design of this research. This provides several perspectives for the chosen problem and approaches that give robustness to the tools and results of this work.

Type of Research

The characteristics of the different scopes of this research are described as well as how they provide a complete perspective about the problem under study. Also, the selected theories support the conclusions obtained by testing the research hypotheses.

This research is exploratory since many features of the oil industry and their effects on the international market are relatively new for Mexico. The approach and the way the chosen variables relate to each other had not previously been put forward for the oil industry. Even though the selected methodology is widely used for its robustness, it allows using different types of variables and exploring in an innovating manner, which provides conclusions based on new theoretical approaches (Torres & Navarro, 2007).

Descriptive studies seek to specify properties, characteristics, and profiles of people, groups, processes, objects, or any other phenomenon under study (Hernández *et al.,* 2006). Therefore, this research is also descriptive because it seeks to state the characteristics of the processes, operations, and properties of PEMEX EP during the 2008-2017 period, in comparison with the results that other countries have in the upstream sector during the same period. The information on the variables is collected and measured for that period.

Correlational research relates variables through a predictable pattern for a certain group or population (Hernández *et al.,* 2006). This research will delve into finding the relationship between EP's capital/labor inputs-outputs and the OTE, TC, and TFP of the 15 main oil producing countries.

The purposes of an explanatory research are to understand the phenomenon and to respond to the causes of events, occurrences, and physical/social phenomena (Torres & Navarro, 2007). The intention of this work is to locate areas of opportunity and strengths in Mexico's oil industry; these are reflected in its main subsidiary company. Therefore, it is essential to find the causes of EP's productivity and efficiency and provide precise conclusions and recommendations on how to trigger positive effects without making structural changes and without altering the current market conditions when compared with other international competitors.

This research has a quantitative approach. This type of research describes the phenomenon by its numerical features, and the data represent quantities of all given characteristics at a certain time or location *(idem).* All data needed to evaluate efficiency and productivity are quantitative because the value of all production factors is stated; thus, the results require statistical and mathematical interpretation in coherence with the selected theories to give an interpretation on PEMEX EP's reality.

All real facts are represented by their corresponding concepts. These concepts describe the basic properties of the objects they represent so that they can be treated as conceptual objects; these concepts are called variables (Torres & Navarro, 2007). A basic classification distinguishes between independent and dependent variables.

The independent variable produces changes in another related variable; for that reason, it is usually defined as a causal variable. The independent variables of this research are capital inputs EW and PW; labor input LF; and outputs PR and TP. The dependent variables are pure technical efficiency (PTE), scale efficiency (SE), and overall technical efficiency (OTE) as the first phase of the research. Then the changes in PTE, SE, OTE and TC are the independent variables of TFP. The latter is the final dependent variable of the analysis concerning this paper.

Scope

The description of facts and their causes seeks new research knowledge through the scientific method in its various expressions. Conclusions must be as general as possible, remain valid, and expose irrefutable evidence (Hernández *et al.,* 2006). However, this process gives way to new knowledge and to the possibility of having several approaches to the same problem with different solutions and descriptions. Depending on the tools chosen for the work and their application cost, the researcher may be impelled to use more specific answers or representative samples. Even if these results are presented objectively, they will have error margins or will only solve part of the general problem. For data processing and creation of the data envelopment analysis as for the analysis of the Malmquist index, specialized software will be used. Then, the results will be analyzed and exposed in the present document.

This research presents Mexico's TFP and efficiency as well as those from the main oil producing countries between 2008 and 2017. It also shows the results of each type of efficiency, both in product volume and with variable returns to scale. Records, documents, and bibliography available on the subject will be used; also, representatives and experts in the subject will be reached for the description of the production processes. This work also shows the contribution of technology and efficiency to TFP.

The chosen methodological tool allows a benchmarking analysis. It compares all production units with those with the best results each year. This helps to determine the unit(s) with best results for more years and the least efficient ones. A slacks review is also carried out to visualize the reasons for the deficiencies.

The present research is oriented to describe the efficiency and productivity of PEMEX EP and the main oil producing countries for the 2008-2017 period. The same review will also be carried out on the TFP of DMU's. This is done to identify the characteristics in each period of those countries with the best performance. Then, this reference will help to identify the causes of the deficiencies for the rest of the nations, particularly the effects on Mexico's oil industry and its upstream sector.

Finally, future lines of research will be proposed. A clear description of the problems facing the world's oil industry in each sector is sought, particularly PEMEX EP and the rest of PEMEX subsidiaries. It is important to know Mexico's oil industry and energy sector in depth; given the strategic value of petroleum exploitation, it is essential to grasp a broader picture for the sake of the country's domestic finances and economic development as well as its participation in the international market.

Limitations

As for historical documentation and access to information, there may be little objective information, or it may be kept secret by company owners, representatives, or managers. Special permissions may also be required and/or costs may be incurred to obtain information or visit a representative. If such costs add up to other research costs, the scope may be limited.

Even if the measurement models chosen are scientifically accepted, new variables or information may be required during the research process; this data may not be available or may have never been included in another research. In addition to modifying variables and their indicators, there may be a need to change the sample or the tools so that the findings specifically describe the upstream sector of the oil industry.

II. Referential Framework for the World Oil Industry

This chapter presents generalities on the oil industry: its classification, its activities, its products, its business cycle, and the types of companies that comprises it. It gives a general overview of the industry at the international level, Mexico's role in the industry, and the role of Exploration and Production in the industry's upstream sector.

General Information on the Oil Industry

The oil industry is considered the largest in terms of value in US dollars (USD). It has a significant concentration of workforce as it employs hundreds of thousands of people worldwide, generating billions of USD annually on a global basis. The regions where the most important NOC's are present contribute significantly to their nations' GDP growth (Harraz, 2016).

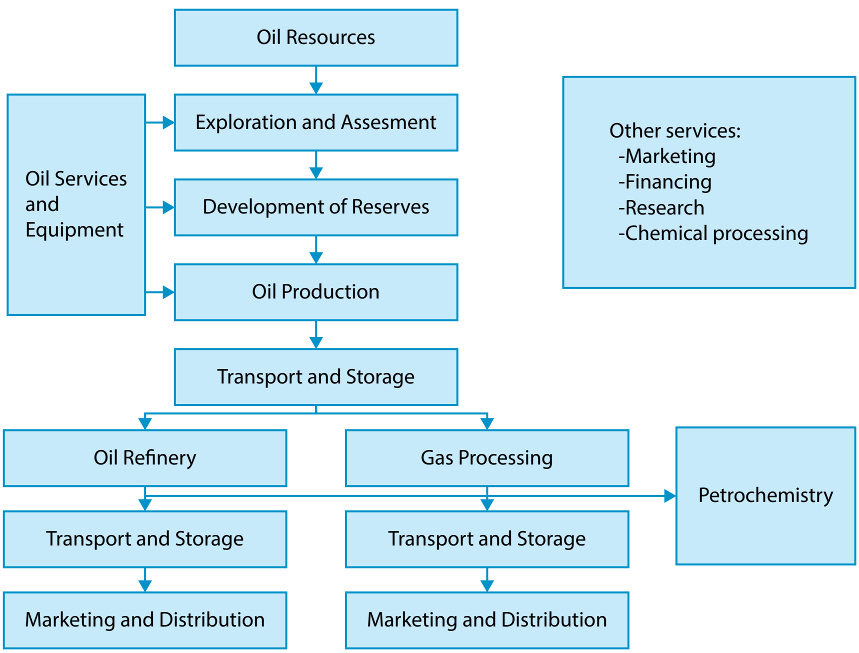
The products generated by the petroleum industry are manifold; fuel oil, natural gas, and gasoline (petrol) hold the highest production volume. Petroleum represents the raw material for a multitude of chemical products such as pharmaceuticals, fertilizers, solvents, and plastics. For this reason, petroleum is a primary input or base for several industries in the most industrially active nations *(idem)*.

Structure of the Oil Industry

The oil and gas industry encompasses a range of different activities and processes that contribute together to the transformation of petroleum resources into finished products; these goods can be used by both industrial consumers and private customers. The activities are inherently connected to each other (whether conceptually, contractually, and/or physically), and these linkages can occur within or across individual firms and national boundaries (WB, 2009).

Part of the complexity of this industry's structure is that most of the oil reserves are controlled by state-owned companies (NOC's) and not by private companies (International Oil Companies - IOC's). Therefore, it is important to define how the industry's main participants are intertwined to understand the functioning and the way in which operations are carried out (Harraz, 2016).

Figure 3. *Oil Industry Operations*



Source: World Bank (2009).

The industry's operations begin by identifying suitable areas to seek petroleum/gas reserves. After the initial exploration, the reservoir is evaluated, developed (exploration drilling and infrastructure project), and then production (hydrocarbon extraction) begins. In Mexico, these activities are generally called Exploration and Production (EP), whereas in other industries they are referred to as Oil and Gas Upstream (API, 2018).

Oilfields require a variety of ancillary services in the exploration and production process, such as: seismic analysis, well drilling, equipment supply, or engineering projects. These services form an important part of the industry's development (over time they have gained considerable experience and importance), and both IOC's and NOC's are domestic and international providers, leveraging their assets to serve more than one client *(idem).*

Transportation (pipelines, roads, railways, ports, etc.) and storage infrastructures are critical at various stages; they are involved in the transfer from production to processing facilities and from there to the final customer. These operations are normally defined as midstream (WB, 2009).

It is necessary to refine petroleum and gas to transform the extracted hydrocarbons into finished goods. The processed products are then distributed to wholesalers or industrial customers. Refining and Marketing (R&M) processes are called downstream[1]. Petroleum and gas products represent the main input for petrochemicals, which explains the historical and geographical link between the two industries (WB, 2009).

A single company may cover one or more operations throughout the entire process, and "integrated" companies may be involved in several successive phases of both EP and R&M; these firms may expand to other operations and cover ancillary services to facilitate operations and offer services/products to other participants in the oil industry. At the national level, the upstream sector is limited by the availability of natural resources, and the downstream sector is limited by the size of the domestic market and the ability to export goods and services (Harraz, 2016).

In recent years, NOC's have held the rights to most of the oil reserves and dominated the *upstream* sector. However, some of the IOC's keep a higher market share such as: BG Group, BHP Billiton, Conoco-Phillips,

[1] Trading, branding, advertising, and franchising are part of the marketing functions.

Chevron, Eni, Exxon-Mobil, Hess Ltd, Marathon Oil, Total and Tullow Oil (Harraz, 2016). As a result, NOC's trade crude oil and gas barrels directly to foreign companies that continue with midstream operations. For instance, PEMEX constantly imports refined products even though it has refineries and a petrochemical industry. PEMEX only allocates about 20% of its barrel production to these domestic activities and produces only 50% of its own gasoline (PEMEX, 2018).

Business Cycle in the Upstream Sector

Bidding or obtaining contracts for exploration and production is the first step that any company must follow to obtain the corresponding license and permits to start operations. Local requirements may vary depending on each country, especially those countries where reserves and operations are carried out by NOC's. In many cases, additional permits are required from local institutions at different levels: tax registration, environmental permits, capacity testing, social responsibility, labor rights, among others (WB, 2009).

Petroleum reserves are the first "product" or asset from which companies derive value based on the reserve classification of the Society of Petroleum Engineers (SPE) standards. Reserves are petroleum quantities (to be recovered) calculated in anticipation of a future trading date. The current economic conditions, the extraction method required, and government regulations are considered. As it is not possible to determine the precise size or even the presence of gas or petroleum in advance, reserves must be calculated by deterministic or probabilistic methods. However, these methods always come with a certain degree of uncertainty. To be counted, reserves are normally categorized as follows: demonstrated reserves or P90, proven reserves or 1P, probable reserves P50 or 2P, and possible reserves P10 or 3P. The latter two respond to a higher degree of uncertainty and/or difficulty of exploiting them (API, 2018).

For petroleum to be considered as a quantifiable reserve (proven in particular) under SPE standards or equivalent, certain information must be available in advance, which means investing in advance. Moreover, estimates of oil reserves not only present uncertainty at some point, but their classification can also even change significantly depending on the understanding of geology, technological possibilities and costs involved, or the ability to invest the revenues obtained (API, 2018).

Many NOC's do not follow or recognize the standards set by the SPE or the Securities Exchange Commission (SEC), and IOC's also underestimate the importance of auditing their suppliers' reserves. For instance, PEMEX did estimate reserves of 60 billion barrels in 1997 but had to reduce them to 22 billion barrels after an external audit, a 64% reduction (WB, 2009).

When hydrocarbons are found in sufficient quantities, the development stage begins. It consists of drilling the reservoir to evaluate and determine the size and marketability of the findings. This is followed by another drilling to start the production and construction of the infrastructure that will connect the reservoirs to local processing facilities or to other marketing routes. Onshore distribution is much simpler, less complex, and cheaper than shallow or deep-water operations *(idem).*

The Midstream Sector, Transport, and Storage

Petroleum and gas must be transported from the production site to the processing facilities and then distributed or traded. Petroleum may also be continuously stored during different stages of the process for different reasons, whether for security, supply, or price speculation (WB, 2009, API, 2018).

Crude oil is stored in tanks and transported by pipeline, truck, rail, or tanker[2] to refineries. Major export ports are often located near the world's oil-producing regions, such as the port of Ras Tanura in Saudi Arabia. This port has the world's largest oil shipping facilities with a capacity of 6 million barrels per day. Import and trading facilities require large storage and shipping capacity such as the Houston Ship Channel, the Louisiana Oil Port, Rotterdam, and Singapore (API, 2018).

Refineries are usually located near the distribution hubs to reduce transportation costs, stay close to the demand for oil products, and purchase

[2] There are great connections through pipelines (oil pipelines) in the world, the Trans-Alaska, or the Druxhba, which supplies from Russia to the rest of Europe, among others; however, oil tankers represent the most used intercontinental transportation method.

crude oil on the open market or directly from producers (WB, 2009). At this point, producers do not necessarily follow all stages, nor they trade the product before processing basic hydrocarbons. Thus, they reduce the need to thoroughly develop their midstream/downstream sectors as they promote trade relationships between NOC's and IOC's.

Pipeline projects require considerable investment and would not be feasible without clearly identifying the goals and long-term commitments of users (domestic and international, public and private), the recovery rates, and a tailored financing. When more than one country is involved, these projects face geopolitical considerations related to procurement or disposal infrastructure, sovereignty, operating and land costs, risk differentiation, security, among others. Once these facts are taken into account, they can substantially improve the viability of future oil projects *(idem).*

The Downstream Sector, Refining and Trading

Crude oil is normally refined into products for consumption; the main categories of these products are fuel oil, gas, kerosene (middle distillates), gasoline, naphtha (light distillates), and liquefied gas. The three main energy uses of oil are transportation, electricity generation, and heating. It is also used for non-energy processes to supply inputs to the petrochemical industry (API, 2018).

Economic development is the main driver of petroleum product consumption patterns across world regions. Fuel oil keeps a considerable demand for industrial uses in developing countries. However, developed countries with economies based on services and transportation of passengers require middle and light distillates (WB, 2009).

The downstream sector absorbs a portion of the global business; it is highly cyclical, and its profitability is very sensitive to changes in the supply and demand of its products. Profitability is mainly measured by the Gross Refining Margin (GRM). It is defined as the difference between the profit earned and the costs of raw materials, labor, maintenance, and working capital (handling). The GRM does not include liquid costs such as depreciation. Therefore, a positive GRM can still be present in a loss-making year; when considering non-liquid (or long term) costs, it is known as the net refinery margin. Both margins are regularly expressed on a per-unit barrel basis. Each margin is different for each plant, yet refineries in the same region tend to show the same value. This is because they serve a market where their products have the same prices, the same varieties of crude oil available to them, and often a very similar technical configuration. Three margins are commonly referred to for comparison: the US Gulf Coast, Northeast European, and Singapore (WB, 2009).

Trading refers to the distribution and sale of refined products, either for wholesale or for industrial retailers. Fuel for retail stations is commonly transported on ground; heating oil is usually delivered directly to industries and homes; kerosene is purchased directly by aviation companies; and residual fuels are sold directly to shipping companies and industrial plants. Trading margins (pre-tax minus *spot* market price[3]) tend to be more stable than refining margins, and the overall profitability of the stations is largely linked to their sales of both non-fuel and convenience goods (API, 2019).

Types of Petroleum Companies

Assessing the competitive scenario of each country's oil sector is complex; it depends on multiple interdependent factors, and the ability of all participants is relevant to generate value. On one end, a pure state-owned monopoly without any foreign participants is considered; on the other, there is a perfectly competitive market without any entry regulation or state intervention. The main classification of oil companies is based on their ownership and operation, which are: National Oil Companies (NOC's), International Oil Companies (IOC's[4]), Operating Companies (exploration and production), and Service Companies (Harraz, 2016).

IOC's are publicly traded corporations; they function like any private company but trading petroleum. They amerged mainly in the USA at the end of the 19th century after the closure of *Standard Oil*, which dominated the market until 1911. Six *"Supermajor"* IOC's are usually referred to; they

[3] In the spot market, both the transaction and the settlement of an operation happen on the same date. However, it is also considered a spot market when deliveries occur in a maximum of 2 days later (Econopedia, 2020).

[4] The World Bank also names them Private Oil Companies (POC).

are publicly traded and have adapted to the integration of NOC's and to price reduction since 1990. This group of companies controlled just 6% of world reserves, while all NOC's control 88% (WB, 2017).

Table 2. *Six "Supermajor[5]" IOC's*

Name	*Location*	*Earnings (billions of dollars)*	*Size of Reserves (billions of barrels)*
Exxon Mobil	Texas, U.S.A.	383	72
Royal Dutch Shell	The Hague, Netherlands	368	20
BP/Amoco	London, United Kingdom	308	18
Total SA	Paris, France	229	10.5
Chevron	California, U.S.A.	204	10.5
Conoco Phillips	Texas, U.S.A.	198	8.3

Source: Authors' design based on BM (2018).

The American Petroleum Institute (API) divides the industry into five categories based on their function. The divisions clarify that the size of reserves is not the only difference between participating companies as the size is not directly related to the profits they can make. NOC's control the upstream sector, and IOC's diversify and make use of all variants such as exploration and production, tankers, refineries, marketing, pipelines, supply and maintenance services, consulting, etc. (API, 2019).

Most IOC's are "vertically" integrated; this means that each company division specializes in different industry segments such as upstream, midstream, and downstream. Supermajor companies are involved in all operations including services but, in some cases, excluding pipelines and marine transportation. The upstream sector remains the main source of revenue for IOC's; their long history in the oil industry has provided them with the necessary expertise to find and develop crude oil. This makes IOC's essential to the industry, even for NOC's. As a result of their dominance in the market, most of their revenue comes from providing these services, which increases both their own reserves and those of their clients *(idem)*.

NOC's or state-owned companies are incorporated very similarly to IOC's; the main difference is that IOC's report their profits to their share-

[5] Supermajor was a reference given to companies that undertook and dominated the market successfully from the 1970s until the 1990s when the collaboration of OPEC countries was consolidated.

holders, whereas the revenues obtained by NOC's are managed by government entities. NOC's control most of the oil reserves of the countries; this happens mainly for two reasons (Harraz, 2016): the first reason is political changes; countries with large oil reserves have gradually snatched the rights that initially belonged to IOC's. Military dictatorships in the Middle East as well as leftist and populist movements in Latin America have succeeded in gaining government in their countries, partly by supporting NOC's and promising the return of petroleum to the people. The second reason for the rise of NOC's is the progress of the oil industry: several oil-rich countries have leveraged their economies by securing profits from their natural resources and relying on contracts with IOC's for extraction and development *(idem).*

The creation of OPEC was a direct response to the speculative power of IOC's. By forming a grand alliance among oil producing countries, OPEC member countries have been able to put more pressure on the prices established by IOC's. In addition, by developing their own means of extracting and refining oil, NOC's have reduced their dependence on IOC's (WB, 2009).

Table 3. *Top 10 Oil Companies by Reserves and Production*

Rank	*Company*	*Oil Reserves (bb/d)*	*Company*	*Production (mb/d)*
1	Saudi Aramco	303	Saudi Aramco	12.5
2	National Iranian Oil Company (NIOC)	300	NIOC	6.4
3	Qatar Petroleum	170	Exxon Mobil	5.3
4	Iraq National Oil Company	134	Petro China Company Limited (PTR)	4.4
5	Petróleos de Venezuela, S. A.	129	British Petroleum (BMP)	4.1
6	Abu Dhabi National Oil Company	126	Royal Dutch Shell plc (RDS.A)	3.9
7	Kuwait Petroleum Corporation	111	PEMEX	3.6
8	Nigerian National Petroleum Corporation	68	Chevron	3.5
9	National Oil Corporation of Libya	50	Kuwait Petroleum Corporation	3.2
10	Sonatrach, Algeria	39	Abu Dhabi National Oil Company	2.9

Source: Authors' design based on WB (2018).

International Context of the Oil Industry

The oil industry is clearly divided in two, OPEC member and non-member countries. The market characteristics that prevailed since the 1960's have caused unequal distribution of oil revenues and export obligations. Therefore, there is now a need to create a coalition to balance the power of private companies over developing economies (Ernst and Steinhubl, 1999).

The Oil Market Prior to the Origin of OPEC

The share of petroleum in the world energy production and consumption has not always been the same; it has undergone a major transformation considering its evolution since the beginning of the 20th century. At that time, Western Europe and the USA supplied their energy needs with their own resources such as coal, natural gas, and the existing petroleum in the USA (Ernst & Steinhubl, 1999).

At the turn of the xxth century, the existence of petroleum in Third World countries was practically unknown, nevertheless this energy resource began to be produced in these regions by 1910. The North American companies made incursions into the Middle East in search for oilfields with higher productivity rates, and they found themselves in the presence of British oil companies. These companies created an international petroleum cartel in 1928; it was made up of the seven largest international oil companies known as the Seven Sisters: Standard Oil of New Jersey (known as Exxon since 1973), Socony Mobil Oil, Standard Oil of California (SOCAL), Gulf Oil, Texaco, Royal Dutch Shell, and British Petroleum. The first five were American-owned, the sixth Anglo-Dutch, and the last British-owned (Ruiz, 2001).

Ruiz (2001) details how these companies had control in terms of exploration, production, trading, and distribution of petroleum, and how they were able to keep prices low. This was due to the low production costs, especially in the Persian Gulf oilfields, and the need to capture the market and displace coal. Another factor was the emergence of new companies outside the cartel and Soviet petroleum in the market.

Until the early 1970's, the individual producer price of crude oil extracted in the US was almost three times higher than the individual producer price of crude oil in the Persian Gulf. On the other hand, US coal was more expensive than US crude oil and tended to set the market price for petroleum. On the contrary, European coal had higher costs than US coal; it remained above the market price and had to be subsidized (Ernst & Steinhubl, 1999).

These developments allowed oil-importing countries to replace their local energy production with lower-priced imported oil. In turn, this led to the closure of several coal mines, resulting in high unemployment rates in the energy-producing sectors. Despite this, the low price from Persian Gulf oil fields did not eliminate other higher-cost energy sources (US crude oil, US coal, and European coal) from the market. This was because the energy market was not a free market (Ruiz, 2001).

In fact, not only was there an oligopolistic structure of oil companies, but the industrialized oil-importing countries also established import quotas, especially the US during the 1950's. Subsequently, taxes were imposed on imported petroleum, and subsidies were established to protect local energy production in both the US and Europe *(idem).*

Despite these measures, the growing consumption of petroleum facilitated the reconstruction and subsequent growth of Europe's and Japan's economies during the twenty-five years following the end of World War II (WWII). Petroleum was more efficiently suited to industry in general, especially transportation *(idem).*

The governments of industrialized countries discovered that these growing petroleum imports allowed more profits to multinational oil companies; therefore, they were able to protect their own fossil fuel reserves and collect significant funds from taxes charged to consumers *(idem).*

Petroleum production increased in the underdeveloped producing countries of the Middle East, South America, and North Africa from 74 million tons in 1945 to 1.5 billion tons in 1974, the time of the energy crisis (Al Chalabi, 1980).

The growing world demand and a continuous deterioration of trade relationships created the conditions for the authorities of the Persian Gulf countries to assume a more active role in direct petroleum exploitation, in the shaping of prices, and in overcoming the discriminatory petroleum trade relationships (Ernst & Steinhubl, 1999).

The Creation and Evolution of OPEC

OPEC was founded during a Conference in Baghdad on September 14, 1960, by five exporting countries: Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela; this gave rise to the first association of countries exporting raw materials (OPEC, 2019).

OPEC was founded during the emancipation of many Third World countries; this period was characterized by a weak price of raw materials, which was particularly evident in the case of petroleum. This situation gave way to an important number of new associations of countries exporting raw materials. Such groups were created for commodities such as coffee, cocoa, natural rubber, bauxite, iron, copper, among others (Al Chalabi, 1980).

In the case of OPEC, its foundation was the product of a tense correlation of forces between multinational oil companies and producing countries. The first few actions date back to the time of WWII. Venezuela achieved the first agreement governed by the "fifty-fifty" principle in 1943; by this means, this producing country would receive half of the profits[6] in addition to the petroleum royalties (Ruiz, 2001).

This action was soon followed by Saudi Arabia, which reached an agreement on similar terms with Aramco company. The Iranian government, headed by Prime Minister Mossadegh, nationalized petroleum operations in 1951 in view of some failed negotiations taking place since 1947. An agreement was reached on similar terms to those countries mentioned above. Two years later, *a coup d'état* overthrew Mossadegh's government, and the Shah of Iran became a fundamental support for industrialized countries in their Middle East policies until its overthrow in 1979 *(idem)*.

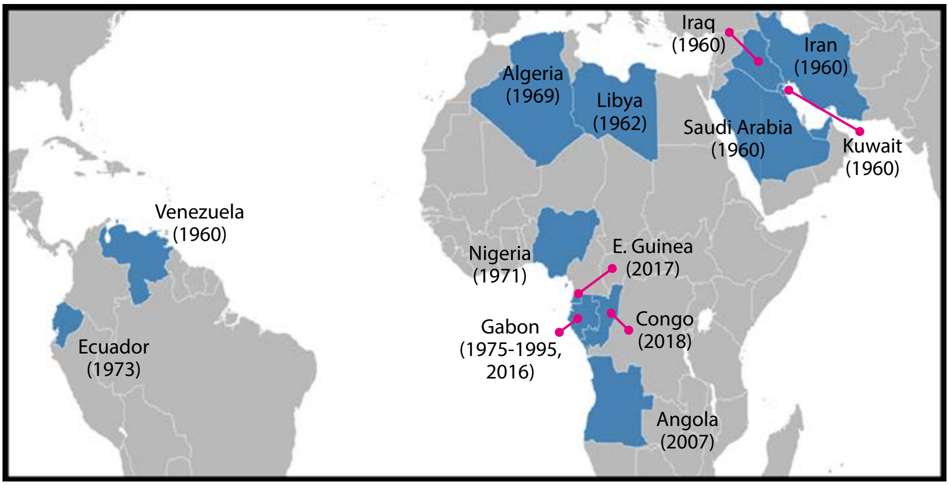
At the same time, the growing demand for petroleum was satisfied by new concessions that producing countries granted to achieve higher profits; the oil royalty was determined based on fixed reference prices. New concessions were granted and generated an oversupply of petroleum. This led

[6] This is the difference between the selling price and production costs.

to a depression in market prices, which in turn caused lower profits for IOC's (Ernst & Steinhubl, 1999).

To increase their profits, IOC's tried to manipulate prices from 1958 onwards by reducing their petroleum reference price. British Petroleum Company made a unilateral decision to reduce this price by 10% in 1959, and a further reduction took place in August 1960. This prompted Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela to create OPEC (OPEC, 2019).

Figure 4. *OPEC Member Countries (Year of Entry)*



Note: Qatar joined in 1961 and its membership ended in January 2019[7]. Indonesia joined in 1962 and suspended its membership in 2009.
Source: Authors' own design based on data from OPEC (2019).

OPEC's initial goal was to confront the policies of reducing reference petroleum prices stipulated by oil companies. Also, their purpose was to avoid the entry of new companies and reduce the competitiveness from other regions, especially Soviet oil for export (Ruiz, 2001).

OPEC's policy has gone through different stages in terms of their internal coordination, and above all, in terms of the circumstances that determined the actions of its members. Although the economies of all member countries are highly dependent on petroleum, there are structural

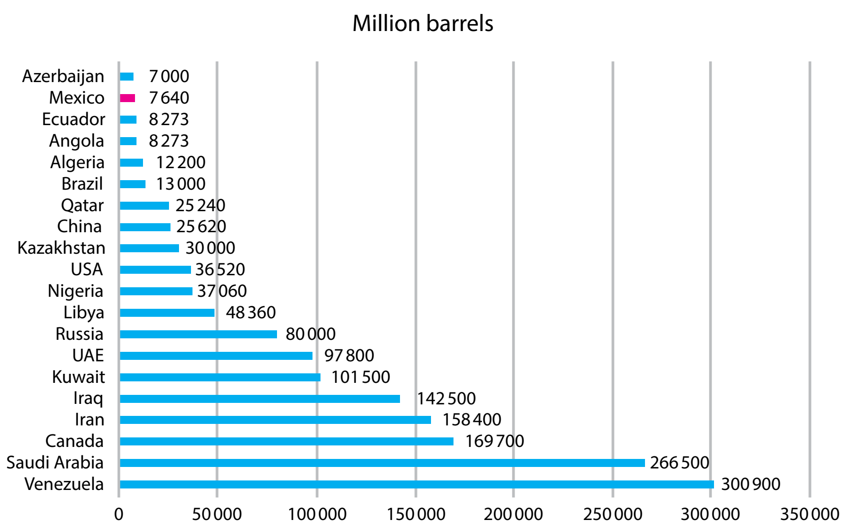
[7] Qatar is considered in this research because the period covers until 2017, a period when its membership was still in force, and its results are included in OPEC's annual reports.

differences that generate important discrepancies in their interests. These differences have also had effects on crude oil prices in international markets.

International Oil Reserves and Production

Both IOC's and NOC's participating in the oil industry contribute to the development of national economies, in one or many countries and in one or many stages. As for the oil industry's upstream sector, the product delivered by the companies during these stages are proven reserves and crude oil barrels[8]. Because of the structural differences between countries, the companies operating in them recover oil reserves and exploit/operate fields in different ways (WB, 2018).

Graph 6. *Top 20 Petroleum Reserves by Country in 2017*



Source: Authors' design based on WB (2018).

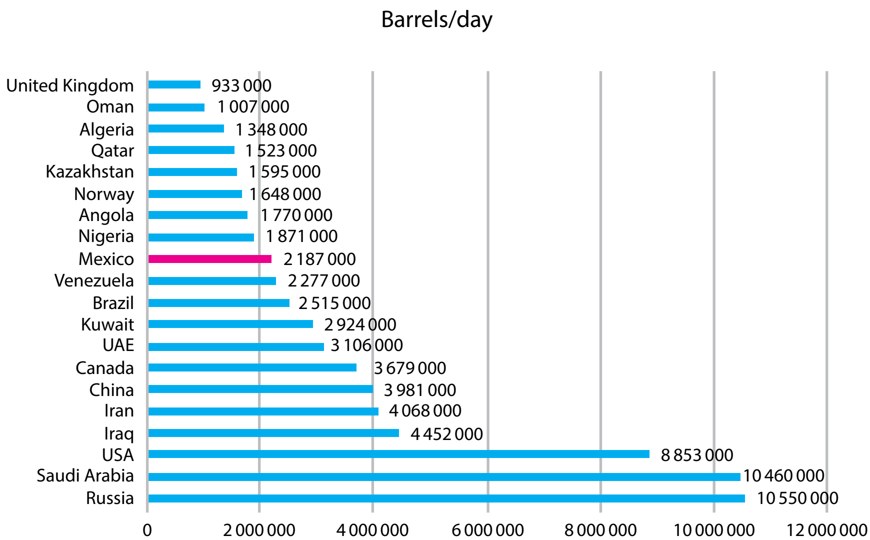
Venezuela, Saudi Arabia, Iran, Iraq, Kuwait, United Arab Emirates, Libya, Nigeria, Qatar, Algeria, Angola and Ecuador are OPEC member coun-

[8] The extraction of natural gas is also included, but for the purpose of this research, the analysis is made on the discovery of deposits and petroleum production.

tries; within this categorization, they own 76.56% of all petroleum reserves. Overall, OPEC countries own 68% of the world's petroleum reserves (WB, 2018).

Few countries hold the rights to their reserves through NOC's in their purest form; exploration and production licenses have been opened, and owner countries grant the right to exploit their deposits to private companies (national and international). However, these companies must share rents and obligations on the production obtained (Eller *et al.*, 2011).

Graph 7. *Top 20 Oil-Producing Countries 2017*



Source: Authors' design based on WB (2018).

In graph 7, OPEC member countries are only responsible for 47.77%. Venezuela is the eleventh largest producing country even though it has the largest proven oil reserves. Another example of insufficient reserve exploitation is Libya; it is among the countries with the largest oil reserves, but it is not among the producing countries (WB, 2018).

In the case of Mexico, there is a considerable ratio between the place it occupies with its petroleum reserves and the place it occupies as a producer country. Most countries are congruent in terms of the place they occupy with their reserves and the place they occupy as producer countries (better or equal position between reserves and production). However, Mexico has limited reserves but a better position as a producer, which may be the result of an exhaustive reserve exploitation without adequate recovery.

III. Theoretical Retrospective of Productivity and Efficiency

This chapter explains the concepts of efficiency and productivity, as well as the difference between the two. In addition, there is a review of the main models that exist in the literature to measure efficiency and changes in productivity. Non-frontier and frontier models are presented, which are classified into parametric and non-parametric. This research relies on the non-parametric models, in particular the DEA, as well as the Malmquist index.

In recent decades, the globalization of the world economy and the liberalization of financial markets have resulted in increased competition. For this reason, the terms efficiency, productivity, and competitiveness are becoming increasingly important for companies and nations. In this sense, companies constantly seek to take actions aimed at improving efficiency and productivity levels, that allow them to cope with such competition. On their end, countries are constantly seeking to improve their competitiveness levels.

Productivity

Productivity has been the subject of multiple approaches and used for several purposes. By the seventeenth century, the physiocrats[1] already used the

[1] Theory based on the idea that economy was a natural phenomenon; this gave rise to the first part of the term "physiocrat" (*physis,* 'nature' in Greek), which meant that market is regulated by itself (Higgs, 1948).

term "productivity" to describe the ability to produce. This definition has been evolving since then; by the 20th century, economists defined it as the ratio between the final product and the factors necessary for its production (Antle & Capalbo, 1988; Eatwell &Newman, 1991; Sharpe, 2002; Maroto & Cuadrado, 2006).

Sumanth (1979) referred for the first time to the work of Quesnay (1846). He affirmed that the greatest satisfaction had to be achieved with the least expense and the least fatigue; this approach is directly related to utilitarianism and presents the background for productivity and competitiveness (Martínez, 2006).

In Adam Smith's *The Wealth of Nations* (1776)[2], some productivity and competitiveness notions are found when he analyzes the causes and repercussions of labor division, worker characteristics, technological development, and innovation. For him, the advantages of labor division are based on the dexterity of workers, time savings for not having to change activities, and the invention of machinery, which facilitates and shortens work efforts.

David Ricardo (1817), in his approaches to the theory of value, absolute advantages, and comparative advantages, detailed the relationship between productivity and competitiveness of countries in the international market; he also developed the idea of diminishing returns in the use of factors.

Kendrick (1961) defines productivity as the relationship between outputs and inputs associated with the production process. He analyzes this relationship in real terms (not in its marginal proportions) through time and based on economic dynamics. He states that productivity is mainly estimated to understand the impact that variables such as investments, specialized knowledge, and technological/organizational changes have on production. This in turn may improve the efficiency of production factors by comparing the change ratios of production frontiers from one period to another.

In their work, Koontz & Weihrich (1998) define productivity as "the outputs-inputs ratio in a specific period with due consideration of quality" (15);

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[2] Smith pointed out that "The nation's annual product of land and labor can only be increased in two ways: through an advance in the productive powers of useful labor or through an increase in the quantity of such labor. The evolution of productive powers depends on the operator's skills and the progress of the machinery with which he works."

this definition lists key elements. First, outputs and inputs refer to results and costs; second, the specific period is temporally framed to make a precise measurement in different times; finally, the consideration of quality refers to the generation of relatively similar products, which is the object of measurement.

In a very similar way, but adding a crucial element for this research, Prokopenko (1987) defines productivity as "The relationship between the output obtained by a system of production or services and the resources used to obtain them" (17). By mentioning production systems, he extends the context of productivity assessment to entities more complex than a company or an individual. This is the case of Mexico's oil industry referred to in this work.

As for an internal approach or microeconomic efficiency, the analysis of productivity focuses on the organization's use of resources but only comparing how similar organizations use them (Giménez, 2004). Therefore, efficiency from an internal point of view is directly related to the productivity level of companies.

Conceptualization of Productivity

A common definition of productivity is the relationship between resources used and products obtained. This refers to the efficiency in the use of resources to produce goods and services in the market (Levitan & Werneke, 1984); thus, productivity can be understood as the relationship between input(s) and output(s).

For Sumanth (1990), production is the activity of producing goods and/or services; it is the quantity of products that are manufactured. On the other hand, productivity refers to the efficient use of resources needed to produce goods and/or services; it is then the relationship between the quantity produced, and the inputs used. Efficiency is the actual ratio obtained and the expected standard production.

Machuca *et al.* (1995), state that productivity is the measurement par excellence of efficiency (technical or economic); this measures the relationship between the production obtained and the number of factors used to obtain it over a certain period of time. Efficiency is defined as the ratio between the useful output and the inputs necessary to achieve it. Therefore, technical efficiency implies inputs and outputs to be measured in physical units. If these measurements are made in monetary value, we are dealing with economic efficiency, which is related to profit maximization and cost reduction.

There are two ways to measure productivity. On the one hand, there are partial measurements that relate production to an input (labor, capital); on the other hand, there are multi factor measurements that relate production to a weighted index of the different inputs used (Martínez, 2006).

When measuring the productivity of different inputs, reference is made to partial productivity. This can be defined as the variation caused in the amount of product generated, caused by a change in the level of consumption of a single input in the production process (Delfín & Navarro, 2015). Measuring the different partial productivities of each production input presents advantages. For example, it is possible to observe the degree to which each production factor or input participated in the increase of production level. The indicator is highly applied to labor-related productivity, which can be measured in terms of people employed and man-hours worked (Maroto & Cuadrado, 2007).

Partial labor productivity is a ratio of output to employed personnel; it reflects how well the employed personnel are being integrated in the production process. It also makes it possible to study changes in labor utilization and occupational mobility, forecast future human resources requirements, examine the effects of technological change on employment and unemployment, evaluate the behavior of labor costs, and compare productivity gains across countries (Ahumada, 1987).

There are also indicators that allow us to measure the productivity of economic factors simultaneously. TFP is a simultaneous measure of efficiency in the use of resources altogether. In a multi-factor analysis of both labor and capital productivity, it is necessary to keep in mind that they are not homogeneous factors. Hernández and Velasco (1990) state that the most common indicator is labor productivity, but there are as many indexes as resources used in production. However, partial productivities do not show the joint efficiency in the use of all resources. So, it is important to have a simultaneous measure of efficiency in the joint use of resources, *i.e.,* TFP (Becerril-Torres *et al.*, 2011).

Total Factor Productivity

The concept of TFP was introduced in the economic literature by Tinbergen at the beginning of the 1940's, and it was developed independently by Stigler in the 1950's. Then, a series of alternative methods for measuring TFP were derived (Baltazar & Escalante, 1996). Subsequently, it was used and reformulated by several authors such as Solow (1957), Kendrick (1961), and Denison (1962). Recently, the contributions of Lydall, Diewer, Christensen, and Jorgenson stand out in this line of research (Hernández & Velasco, 1990).

The methods used for productivity estimation can be classified as follows:

- *TFP as a measure of productive efficiency or non-parametric.* TFP increases if the output grows at a higher rate than do inputs, which makes TFP an indicator of output growth not explained by the increase in inputs. This is defined as a "Solow residual" (Solow, 1957; Kendrick, 1961; Hernández & Velasco, 1990).
- *TFP as a non-parametric measure of technical change.* TFP is considered as the increase in the productive capacity of an economy that is a consequence of technical change or the shift in the production function. For this approach, a shift in the production function leads to a variation in TFP (Baltazar & Escalante, 1996).

The concept of TFP arises from the need to find a measure of efficiency in the joint use of resources. This helps to identify which of the two factors of the product caused a shift in the production function, which is the result of a productivity increase or decrease (Ayvar, 2006). It is also used to measure how changing the quality of the factors used may influence productivity changes, whether tangible or intangible (technological change, structural change, investment in research and development, training, etc.) (Kendrick, 1961).

Measuring Productivity

There are four major methods to measure productivity (Mawson *et al.,* 2003; Singh *et al.,* 2000; Mahadevan, 2002), which are: the Growth Accounting theory, econometric methods, the Index Number theory, and non-parametric frontier functions; the latter will be used in this research.

The first two are generally applied to aggregate time series data and provide technological change and TFP indicators. The latter two are mostly applied to microeconomic point-in-time data to measure relative efficiency. However, the goals and functions can also be interchanged (Maroto & Cuadrado, 2007).

The Malmquist Index and TFP

Malmquist (1953) introduced his indexes in the Consumption theory; he created quantitative indexes from the quotient of distance functions. This proposal was later applied to productivity measures by Caves *et al.* (1982), in a production function context and by Färe *et al.* (1998) in a non-parametric (DEA) context.

Distance functions are functional representations of multi-product and multi-factor technologies that only require data related to the quantity of outputs and factors. The Malmquist index is a "primary" index of productivity growth that, in contrast to the Torqvist index, does not require data related to the total cost or income rate to aggregate inputs and outputs; it is able to measure TFP growth in multi-product situations. It does not require assumptions about profit maximization or cost minimization either, so it is free of functional form misspecification.

Efficiency

The concept of "effectiveness" is closely related to that of efficiency; effectiveness is the fulfillment of objectives while efficiency is the achievement of goals with the least number of resources (Koontz & Weihrich, 1998). Adding this definition to the concept of productivity, efficiency can be understood as the relationship between costs and benefits with the purpose of performing tasks using resources in the most rational way possible (Navarro & Torres, 2004).

The studies of Prokopenko (1987) and Sumanth (1990), relate these concepts, delimit efficiency as part of productivity, and state that productivity requires an efficient use of resources (inputs) when producing goods and services (outputs). Also, to support the scope of this research, efficiency is analyzed in Pareto's terms. Thus, a resource-allocation mechanism is efficient if no other allocation allows everyone to enjoy at least the same welfare and strictly improves somebody's life standards. The efficiency of consumers' welfare and the production achieved are to be considered; producers should be allowed to position services and products in a larger part of the market without negative effects on the rest of the population.

The concept of efficiency has been studied worldwide from a technical and economic point of view. Technical efficiency is normally measured through productivity ratios, that is, the result of dividing the production achieved by the productive factors employed. This type of measurement is carried out in physical terms (without taking into account the cost of productive factors or the product's price). On the other hand, economic efficiency is related to profitability rates in monetary terms, that is, the economic income divided by all financial resources used to obtain such income (Giménez, 2004).

The Typology of Efficiency

Farrell (1957) was the first to introduce a theoretical framework to study and measure efficiency. He visualized efficiency from a real and not ideal perspective, where each productive unit is evaluated in relation to others taken from a representative and homogeneous group. Thus, efficiency will be relative and not absolute; the degree of efficiency achieved by a company will be the level of divergence from those considered efficient.

Technical Efficiency

For Koopmans (1951), technical efficiency is when an increase in any output entails a reduction in at least another output or an increase in any input, or, if a decrease in any input entails an increase in at least another input or a decrease in any output.

Subsequently, Banker *et al.* (1984) divided technical efficiency (now overall technical efficiency) into pure technical efficiency and scale efficiency. Pure technical efficiency shows the extent to which the production unit under analysis takes the maximum yield possible out of the physical resources available. Scale efficiency is relevant when the production technology presents variable returns to scale; this type of efficiency shows if the production unit analyzed has reached the optimal scale point. As for the proportion of yields obtained per physical unit, these can be classified as follows:

- *Constant returns to scale.* It means that if the quantity of one of the factors is increased, the production increases in the same proportion.
- *Increasing returns to scale.* By increasing one of the factors, production increases in a greater proportion.
- *Diminishing returns to scale.* By increasing the amount of one of the factors, production increases in a smaller proportion.

The Overall Technical Efficiency (OTE) is the result of multiplying Pure Technical Efficiency (PTE) by Scale Efficiency (SE). In this logic, dividing OTE by PTE yields the value of SE and can be reproduced in the basic DEA model (Ayvar, 2006). The perspective is broadened this way to observe whether the returns obtained by the countries in relation to their factor combination depends on their industry size.

Trillo (2002) states that the study of technical efficiency focuses on the use of human or capital resources during the production of one or more goods and services. This is based on the use of physical units, which implies that the cost or price of factors and the valuation of the income obtained from production are left out of the analysis.

Thus, technical efficiency considers the technological restrictions presented by productive units; there are only certain factor combinations viable to obtain a given amount of production, so companies must circumscribe to adopting production plans that are feasible from a technological point of view (Varian, 1998). The term technical efficiency differs from productivity;

the latter refers to the quantity produced per input, while the former refers to how well a productive unit performs with the existing technology.

Therefore, a company is considered efficient if it obtains the maximum possible production using certain number of resources, but it is inefficient if it obtains less production using that same number of resources. The study of efficiency is based on the frontier production. A company's technical efficiency index is calculated by the ratio between the actual production and the frontier production; the latter would have been reached if all production factors had been used in a totally efficient way. In this sense, the frontier production will be found at the maximum value attainable by each company, given certain production factors (Dios, 2004).

Allocative Efficiency

In microeconomics, there is allocative efficiency when resources are not wasted, and the Pareto Principle is fulfilled. Scott and Parkin (1995) perceive three conditions to achieve allocative efficiency:

- *Economic efficiency.* It entails technical efficiency as well as the use of production factors in proportions that minimize costs.
- *Consumer efficiency.* Occurs when consumers manage to improve their welfare within a certain budget.
- *Equal marginal cost.* Cost of producing an additional output unit, including external costs[3], and cost of the marginal social benefit, *i.e.*, the benefit of an additional consumption unit, including external benefits[4].

In allocative efficiency, costs and benefits are normally established in monetary terms. Therefore, allocative efficiency happens when the monetary income corresponds to the maximum benefit, and the monetary expenditure on inputs is minimized (Yarad, 1990; González-Páramo, 1995). In a microeconomic sense, Bosch (1999), points out that efficiency is reached when the manager of a productive unit has reached the production

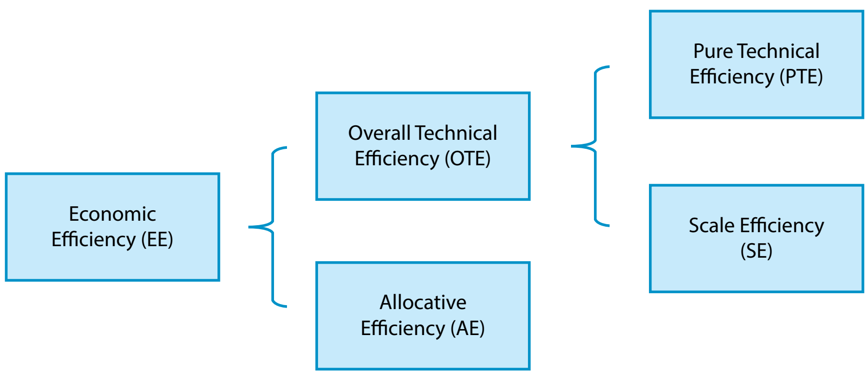
[3] External costs are not borne by the producer but by other members of society.
[4] External benefits are those received by people other than the end consumer.

frontier by choosing a factor combination that allows to minimize production costs.

Overall Economic Efficiency

Farrell (1957), divides efficiency into two components: technical efficiency and allocative efficiency; he then defined economic efficiency as "the efficiency of an allocation from a technical and allocative point of view" (5). Also, Pinzón (2003), defines economic efficiency as the achievement of maximum production at the lowest possible cost. Thus, the goals of a company or productive unit are: *1)* to minimize production costs, *2)* to maximize income, and *3)* to maximize benefits at the minimum cost. So cost, income, and profit efficiencies depend on both technical and allocative efficiencies.

Figure 5. *Types of Efficiency*



Source: Authors' design based on Giménez (2011).

Economic efficiency is given by the relationship between the minimum cost (frontier) and the actual supported cost. Therefore, a company is economically efficient when it reaches the best possible combination of the necessary inputs and their market prices (Dios, 2004).

Efficiency and Productivity

The terms efficiency and productivity are often confused and used as synonyms. Although measures of efficiency and productivity are directly related, they represent different concepts of performance in economic agents. TFP is the ratio between a function that aggregates outputs and a function that aggregates inputs. On the other hand, efficiency is based on the comparison of output/input values and relative optimal values, which are taken from evidence provided by other firms (Sarmiento, 2007).

Regarding efficiency, there are many conceptualizations that generally express the relationship between inputs and outputs. The efficiency of a DMU is understood as the comparison between the observed values and the optimal values of inputs and outputs. This comparison can be carried out in three ways: first, by comparing the maximum achievable output for a given level of inputs and the one achieved (output orientation); second, by comparing the minimum level of inputs necessary for a given level of outputs and the one used (input orientation); and third, by combining the two previous ones (Giménez, 2004).

This type of efficiency, which refers to the levels of inputs and outputs in physical units, is known as technical efficiency. If inputs and outputs are measured in terms of costs, revenues, or benefits, *i.e.,* considering their prices, the measure is called economic efficiency (Navarro, 2005).

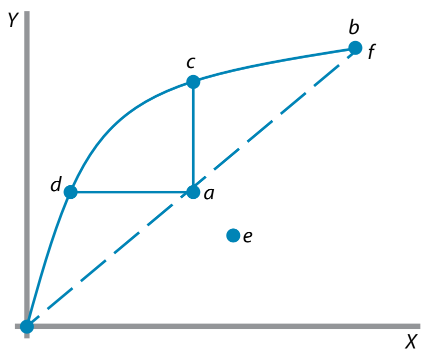
Efficiency is a relative value since it is based on comparing units that are evaluated under the same characteristics. Therefore, it assumes that they have a similar functioning between them. It compares the way in which the units make use of their resources, and most importantly, it assumes that they should seek the same purposes (Guio & Monroy, 2003).

A unit is efficient if there is no other unit or combination of units that generates the same number of outputs with a lower level of inputs or generates a higher number of outputs with the same level of inputs. Therefore, it is implicitly recognized that there is at least one efficient point or unit which is in the PPF. The efficient units establish an ideal efficient performance frontier; the efficiency frontier is given by the maximum combination of outputs that can be produced for a given level of input, or the minimum number of inputs that can be used to obtain a given combination of outputs. The value of efficiency can be estimated based on this frontier (Calderón, 2007).

The study of efficiency aims at identifying those productivity features that are attributable to the capacity of using resources to control costs and generate income and benefits (Pérez & Maudos, 2001).

The productivity of a DMU can be defined as the ratio between its outputs and inputs expressed in physical units. This quotient evaluates the degree of use of all physical resources involved. Thus, production may be the only way to measure a DMU's performance when there is no data on other similar units. The value of a DMU cannot be compared with others (under the assumption that there are no other similar units), but its evolution over time can be analyzed to know if it has improved or worsened with respect to previous periods. In contrast, when information is available from other similar DMU's for the same period, both productivity and efficiency could be used to compare the performance of a DMU with respect to others (Giménez, 2004).

Figure 6. *Productivity and Efficiency*



Source: Giménez (2004).

Figure 6 shows the case of a DMU that produces a single output *(y)* by consuming a single input *(x),* where the curve *(f)* represents the production function. DMU's *a* and *b* have the same productivity. DMU *b* is efficient because there is no other one producing a greater amount of output with the same or less input or producing the same amount of output with less input. On the other hand, DMU *a* is not efficient since its optimal output would be that of DMU *c* with its own input level, or it could produce the same amount of output with the same input as DMU *d.* Finally, DMU *e* has a higher productivity than *a* and *b,* and just like *a,* it is not efficient. Then the inefficiency of a DMU can be observed from the point of view of inputs and outputs (Giménez, 2004).

Estimation of Efficiency

Two types of methods are used to measure and study efficiency, non-frontier and frontier methods (Navarro, 2005). In the latter, several empirical studies have contributed tools to define how a productive unit is compared and how the frontier that measures the deviation of efficiency is formed. This section describes the most representative ones as well as their main characteristics.

Methodological Alternatives for Measuring Efficiency

Regarding measurement, efficiency is a relative concept (Førsund & Hjalmarsson, 1979), so the result of an economic unit must be compared with a standard. In this sense, the measurement of efficiency requires two stages (Sellers *et al.,* 2002).

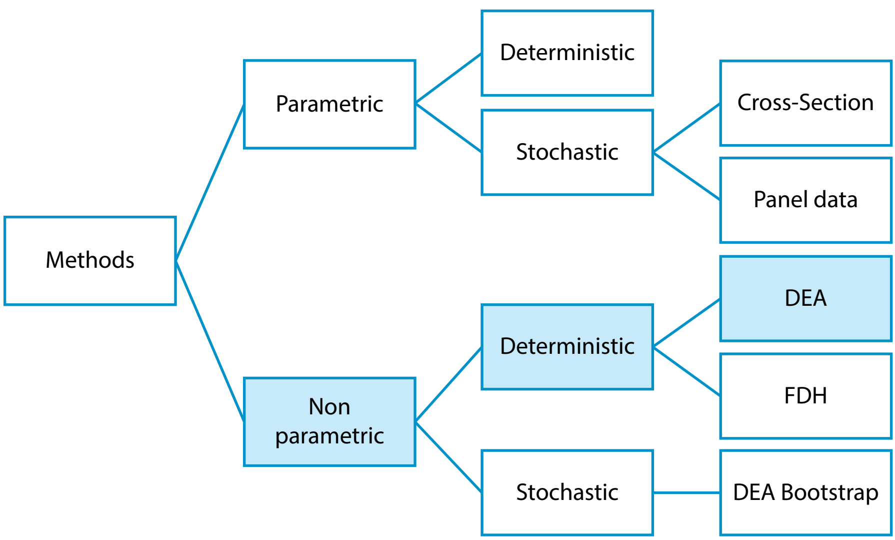
1. First, there must be a standard reference function indicating the maximum output level attainable from different input combinations given a fixed production technology. The reference function or frontier function can be either a production function or a cost function, or even a profit function.
2. Second, the results obtained by each production unit must be compared with the standard frontier, so that the existing deviations (or ratios) will be considered inefficient behavior.

This procedure can be followed through different methods which are classified according to their parametric or non-parametric character as shown in Figure 7.

The calculation of efficiency basically involves three problems (Lovell, 1993).

- How many and which inputs and outputs should be included in the analysis. The inefficiency of a production unit may be due to the non-inclusion of all inputs. The inefficiency of a production unit may be due to the non-inclusion of all inputs and outputs according to Stigler (1976). There is a higher possibility of excluding one of them if the technology used is unknown.
- How they should be weighted in case that a variety of inputs and outputs are to be aggregated. As mentioned, the most common solution is the use of prices as a homogenizing element, but sometimes these are not available or are unreliable, especially when evaluating public sector units,
- How the optimal performance level should be determined for comparison. This is a rather complex problem. In theory, it seems clear that the optimal behavior should lie on the production frontier, but this is a theoretical concept, not observable.

Figure 7. *Methods for Measuring Efficiency*



Source: Barrow & Wagstaff (1989).

It is also possible to break down these methods into frontier and non-frontier. In this research, we apply deterministic non-parametric frontier methods (DEA), so the characteristics of the selected method will be pointed out and the differences between methods will be clarified.

Non-Parametric Methods

In non-parametric approximations, it is not necessary to establish a technology of parameters that determine a priori the relationships between inputs and outputs. It is only necessary to define certain properties that must be met by the production. Thus, the data are enveloped and determine whether each point belongs to the frontier under those properties (Farrel, 1957).

The estimated frontier is more flexible than the parametric frontier; it is formed by those units in the sample that produce the highest quantity of outputs with the lowest quantity of inputs. The estimation of the frontier is deterministic in most models (deviations from the frontier are produced only by technical inefficiencies); linear programming techniques are used for its estimation (Murillo, 2002).

Giménez (2011) lists the main characteristics of non-parametric frontier models:

- They construct an empirical frontier from observed data, without assuming any functional form based on the Pareto's efficiency criterion.
- They measure the overall efficiency of a set of decision-making units (DMU's) using multiple inputs and outputs.
- They are based on microeconomic concepts (production theory) but with full applicability and without the usual simplifications.
- They measure relative efficiency.
- The units located on the frontier are deemed efficient, and the rest are considered inefficient.
- The level of inefficiency is determined based on the distance from the frontier.
- Orientation towards inputs (employers' view) or outputs (trade union view).

Berger & Mester (1997) and Berger & Humprey (1997) explain that non-parametric methods have some assumptions that can be problematic; they generally do not consider input prices, so they only measure technical inefficiency rather than total inefficiency. Furthermore, non-parametric techniques do not consider the possibility of random errors in inefficiency measurements. For this reason, the efficient frontier, and practices of any DMU, are attributed only to inefficiencies presented by them.

However, non-parametric models can also be classified as stochastic or deterministic, depending on whether the model specification allows the inclusion of random disturbances as possible causes of inefficiency.

Non-Parametric Deterministic Methods

Afriat (1972), provided the theoretical framework for Farrel's proposal to build a convex envelope using mathematical programming techniques. Here, the efficient units define the limits of the frontier depending on the result from a revenue maximization or cost minimization model.

This method does not require specification of a functional form for the frontier. For this reason and because it does not consider the existence of a disturbance term, it is called non-parametric. Therefore, it is considered deterministic because no shift is allowed in the frontier, which provides great operational flexibility (Navarro, 2005).

The main disadvantage of this approach to the efficiency measurement problem is that the frontier is supported by a subset of supposedly efficient observations; it is very sensitive to the existence of *outliers*[5]. The outliers can at first be classified as influential observations, but this does not mean that they really are. Another disadvantage is that it is deterministic; any unit that deviates from the frontier is considered inefficient, hence the researcher must try to minimize measurement errors in the variables *(idem)*.

There are two possible non-parametric estimation procedures within the models with deterministic frontier: Data Envelopment Analysis (DEA) and Free Disposal Hull (FDH). The main difference between these two tools

[5] Unit that does not follow the general behavior of the units analyzed.

is that DEA requires convexity in the set of production possibilities while FDH does not. DEA is the technique that has been used the most. However, both techniques are equally appropriate for assessing producers' actions when more than one output is produced and in cases where prices are unreliable or unknown (Murillo, 2002).

Table 5. *Approaches to Measuring Efficiency*

Non-parametric boundaries (DEA)	*Parametric boundaries Econometric approach*
Deterministic (with recent advances in stochastic DEA).	Stochastic
Oriented to decision making for management. Its origin is in administration science.	Strong political orientation from its origin (Lovell, 1995). Theoretical bases in economic science (production theory).
Calculations: Solving linear programming problems.	Calculations based on statistical inference procedures.
It generally constructs production boundaries to measure technical efficiency.	Production or cost frontiers are estimated to measure technical or allocative efficiency or both.
It does not require specifying a certain functional form of the production function. Very flexible, valid for any "technology" of transformation of inputs and outputs.	It requires specifying a certain functional form of the production or cost function (Cobb-Douglas, constant state elasticity, trans log...). Increasingly tends to consider flexible functional forms, which have a cost in terms of over-parameterization and consumption of degrees of freedom.
Method designed to evaluate production units that produce multiple outputs.	The production frontier does not easily accommodate multiple outputs. The cost frontier does.
Requires only input and output quantity data. Especially useful for utilities that operate outside a market or whose unit input prices are unknown.	To estimate the cost frontier, input quantity and price data are needed.
A best practice frontier is constructed for each production unit, which is formed by other efficient production units that they "imitate".	The estimated frontier, of which the efficient productive units are part, is unique for the whole sample.
Flexible treatment of the effects of scale of operation. Admits that each productive unit stresses its "most productive" size.	More rigid treatment of the effects of scale of operation: a common optimal size (sample average) is estimated.
Confuses statistical noise with inefficiency by constructing deterministic frontiers. Results can be very sensitive to positive outliers (atypically productive production units).	It considers elements of good and bad luck in achievement separately from the efficiency measure, but it requires assumptions about certain probability distributions for both random components of the model. The results may be sensitive to these assumptions.

Source: Ortún Rubio *et al.* (1999).

Non-Frontier Methods

Non-frontier methods recognize two aspects: those based on index numbers, and those in which the ability of productive units is verified to match factor productivity to their normalized prices[6]. The latter are limited since they require an already established functional form to verify hypotheses; their main drawback is that they do not allow studying efficiency based on each productive unit.

The index number is "a quantity that shows, by means of its variation, the time or space changes of a magnitude that is not in itself susceptible to direct measurement or direct observation in practice" (Sumanth, 1990). Thus, assessing efficiency through this method allows to determine a productive unit's efficiency behavior in a certain period of time. However, these tests are limited because the combination of units escalates exponentially with the number of units to be compared; it requires the assumption of existence of efficient allocations in the units under study, and it does not reduce the number of indicators to be compared, it simply corrects them. Even evaluating each productive unit and even complying with the hypothesis of cost minimization, it does not help to identify the sources of inefficiency.

Frontier Methods

The methods of deterministic non-parametric frontiers, deterministic parametric frontiers, statistical frontiers, and stochastic frontiers derive from Farrel (1957). The specification of the functional form for technical and allocative efficiency refers to the frontier established by a production or cost function, respectively.

The main idea of the frontier methods is to establish an accurate frontier based on input consumption and output generation in a set of units[7] (DMU's). This frontier will include the efficient units, *i.e.,* those with an efficiency index equal to 1; the DMU's below the frontier will be considered inefficient and their efficiency index will be less than 1. Thus, inefficiency will be measured as the distance between the frontier and the units below it (Navarro, 2005).

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[6] Price distribution of inputs used in the production of one or more products.

[7] The frontier concept is more general than the production function concept, which has been considered fundamental in economics; the frontier concept admits the possibility of multiple production functions, one for each DMU, and the limits of the frontier consist of tangential supports to the most efficient members of a set of such frontiers (Cooper *et al.,* 2004).

As for deterministic non-parametric frontiers, Afriat (1972), provided the necessary paradigm for Farrel's proposal to construct a convex envelope using mathematical programming techniques. Here, the efficient units define the limits of the frontier and determine where all other firms are located, either above or below the frontier. According to this, the result is obtained from a model of revenue maximization and cost minimization. They do not require the specification of a functional form for the frontier (non-parametric) or the existence of a disturbance term (deterministic).

Regarding the methods of deterministic parametric frontiers, Farrel (1957), also proposed the creation of a convex envelope from a common functional form for all productive units; it had the advantages of applying a mathematical expression of the frontier. Førsund (1974), presents models that minimize the difference between the observations and the predictions obtained from the imposed functional form; it was done either using a quadratic loss function of the errors or in absolute value of these. In either case, mathematical programming techniques are used to estimate the parameters.

The deterministic statistical frontier models take the models of deterministic parametric frontiers and impose a hypothesis of distributional character on the deviation to estimate them; they generally and uniquely use statistical methods of maximum likelihood[8] (Navarro, 2005). Its main limitations are that it requires a *gamma* correction[9], which needs many observations; and the function of the envelope is at the discretion of the researcher even though Greene (2008) suggests a trans log function to reduce subjectivity. Even then, it doesn't completely do so.

Meeusen & Van den Broek (1977), proposed a model in which the distance between the frontier and the productive unit could mean that the frontier itself is stochastic due to measurement problems of the variables; these disturbances are to some extent out of control. To incorporate these new concepts, stochastic frontier models employ an additive error composed of a normally distributed stochastic variable and an asymmetrically distributed stochastic variable. Despite providing a more rigorous treatment, it is

8 Usual statistical method for adjusting a model and estimate its parameters.

9 Assuming that the data distribution is gamma requires many observations before achieving an asymptotic sample.

not possible to identify the technical efficiency of the allocative efficiency; it requires a large amount of data and makes it difficult to determine the production unit's degree of inefficiency.

Authors like Charnes & Cooper (1962), Aigner & Chu (1968), and Afriat (1972), followed the concepts of Farrell (1957). They developed the Data Envelopment Analysis (DEA) frontier model, structuring it as a linear programming model. This model works with constant returns to scale (CRS) and has three characteristics: *1)* They reduce the situation of multiple inputs and outputs (for each firm) to that of a single "virtual" input and a single "virtual" output; *2)* The ratio (virtual output/virtual input) provides an efficiency measure; *3)* In terms of mathematical linear programming, they seek to maximize this ratio (objective function) subject to the normalizing restriction that the ratios of all firms are less than or equal to 1.

To calculate the relative efficiency of a decision-making unit (DMU) where its dual problem is solved with constraints on the inputs, the dual illustrates the nature of the relative efficiency given that the stacks or non-radial reductions of inputs are obtained in case they exist. For the unit to be considered efficient in Farrell's sense, it must be equal to 1, and the slack must be equal to 0. Later, Banker *et al.* (1984) suggest an extension of the model towards situations of variable returns to scale; they do so by modifying the programming problem with a new restriction regarding the sum of yield variations, which are compared only with productive units of similar size. With this modification, it is possible to differentiate pure technical efficiency from scale efficiency. To do so, the two models, CRS, and variable returns to scale (VRS), must be calculated with the same data; it is scale inefficiency if there is a difference between the two measures for one DMU, and the value of the inefficiency is the extent of such difference.

Data Envelopment Analysis for a Deterministic Efficiency Analysis

In its basic operational form, DEA is a methodology used for the comparative efficient measurement of homogeneous units, *i.e.,* those with the same purpose and economic rationality. Based on inputs and outputs, DEA orders all agents by giving them a relative efficiency score. The agents obtaining the highest output level with the least number of inputs will be the most efficient of the group and, therefore, will obtain higher scores (Barrios, 2007).

The DEA estimation method evaluates the efficiency of a decision-making unit (DMU) by referring to the "best" producer. It considers a production unit as efficient and therefore belonging to the production frontier, *i.e.*, the unit produces more of a certain output without diminishing the rest and without consuming more inputs, or it uses less of a certain input without using more of the rest, and it generates the same outputs. The idea is to compare each non-efficient unit with one that is efficient and has a similar production technique, that is, that uses inputs in similar proportions to produce similar outputs. The estimation of efficiency coefficients under the DEA scheme can be classified into two types (Embid, 2011; Delfín & Navarro, 2015):

- Input-oriented
- Product-oriented

The input-oriented model seeks to minimize inputs and produce a certain level of output. The output-oriented model, on the other hand, seeks to maximize outputs given a certain number of inputs *(idem)*. It is also possible to have a non-oriented model, which seeks to obtain the maximum number of outputs with the least number of inputs (Navarro, 2005). The difference lies in the restrictions imposed on the linear programming technique.

The formulation of the model is established in the DEA; it calculates the production frontier and evaluates the efficiency of a sample of DMU's. In this type of analysis, the relative efficiency for each DMU is calculated by comparing its inputs and outputs with all other DMU's.

DEA is a frontier method that evaluates production with production functions; the production function is understood as the maximum level of output achievable with a certain combination of inputs, or the minimum level of inputs necessary to produce a certain level of output. Since it is a non-parametric method, it does not require any hypothesis on the production frontier; a unit's efficiency is defined based on the units with the best performance. The possibility of analyzing the best performance gives rise to benchmarking instead of analyzing the average performance[10], as regression analysis does (Arieu, 2006).

In addition to measuring relative efficiency, the DEA can be used to obtain *(idem)*:

- An empirical envelope surface, which represents the behavior of the best performing DMU's.
- An efficient metric to compare results.
- Efficient projections on the frontier for each inefficient DMU.
- An efficient reference set for each DMU defined by the efficient units closest to it.

The basic DEA models are those that consider constant returns to scale and those that operate with variable returns to scale. In the models with constant returns to scale, the units take as DMU the reference with the highest productivity among those observed when calculating their relative efficiency *(idem)*.

Table 6. *Advantages and Disadvantages of DEA Models versus other Models*

DEA	Stochastic Frontiers
Advantages	*Disadvantages*
It does not specify the functional form.	A production and distribution function of random variables must be prefixed.
Provides useful information for management (comparison groups, objectives follow-up).	Less information (no slacks).
The variables of the multi-production model do not need to be weighted a priori.	Output weights (frontier function).
A single outcome (Pareto's optimal).	Possibility of local optimal.
Disadvantages	*Advantages*
Deterministic model.	Random error-inefficiency division.
Complication in obtaining test (sensitivity analysis of the model).	Goodness-of-fit test for the models and significance test of parameters.
Extension of indicator analysis.	Causality analysis.
High influence on the outlier frontier.	Less sensitivity to extreme behavior.

Source: Trillo (2002).

[10] In methods with linear regression techniques, the regression is made based on the mean population. Therefore, the mean behavior is being analyzed in these cases (Hernández *et al.,* 2006).

Dynamic Analysis of Productivity and Efficiency

The techniques described so far allow capturing the performance of DMU's at a specific moment in time. However, there are extensions of these techniques that allow change analysis on DMU efficiency over time. The dynamic analysis allows to know the evolution of DMU's in different periods of time and their position with respect to the frontier, which is also subject to change or displacement (Cuddington & Moss, 2001).

There is abundant literature on dynamic analysis using non-parametric frontier models, especially for the DEA case. The mainly used techniques are Windows Analysis[11], related to the use of time-dependent DEA; and the Malmquist Productivity Index (1953). Sten Malmquist's concept, introduced in 1953, has been studied and developed in the non-parametric framework by authors such as Cooper, Seiford, & Kaoru (2007).

Malmquist Index

Non-parametric frontier techniques are commonly used to measure both efficiency and productivity of decision-making units (DMU's). The measurement of technical efficiency using this method is based on estimating distance functions, as with productivity indexes. The Malmquist index is generally used for this type of measurement, which is calculated through DEA.

The concept of the Malmquist index was introduced in 1953; it has been studied and developed by several authors since then. The Malmquist Index of Productivity Change was defined by Caves *et al.* (1982); later extended by Färe *et al.* (1994) by merging Farrell's efficiency measure (1957).

Under the same idea, the temporal analysis techniques based on the Malmquist index explain the changes produced in a unit's efficiency from

[11] The name and the basic concept were given by Klopp (1985), who demonstrated these techniques as Chief Statistician of the U.S. Army Recruiting Command. This work was later incorporated into his doctoral dissertation, "The Analysis of Production Systems Efficiency with Multiple Inputs and Multiple Outputs," at the University of Illinois at Chicago.

one period to another; it is because of the frontier movement and the movement of the units analyzed (Giménez, 2004).

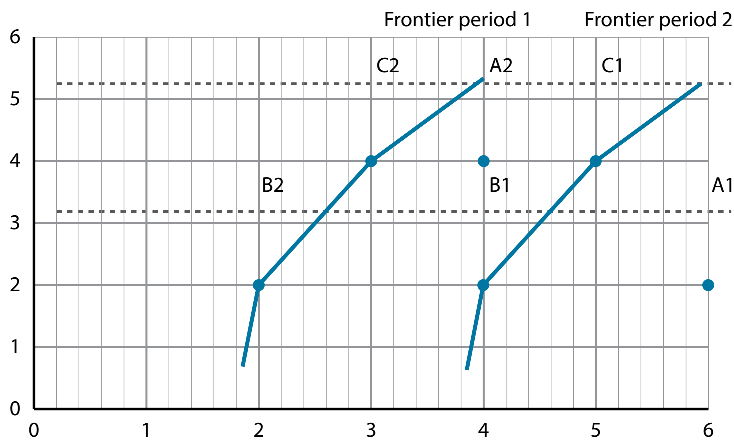
To define the Malmquist Productivity Index, it is necessary to define the distance function (the output-oriented distance function) with respect to two different time periods (Guzmán & Reverte, 2008). Thus, the Malmquist index (based on output) is defined as the ratio of two distance functions (output). Distance functions are functional representations of multiple outputs, multiple input technologies that require only input and output data. Therefore, this index is a primary measure of productivity change. In contrast to the Tornqvist index, it does not require to share cost or income for aggregation purposes, and yet is capable of measuring TFP growth in a multi-input and multi-output configuration (Radam *et al.,* 2008).

The Malmquist index of TFP is used to measure the impact of productivity change. Therefore, the Malmquist index evaluates a DMU's productivity change in two time periods and is an example of "comparative statics" analysis (Becerril-Torres *et al.*, 2011). It is defined as the product of the Catch up and Frontier-shift concepts. The term Catch up refers to the degree to which a DMU improves or worsens its efficiency; the term Frontier-shift reflects the change in efficient frontiers between two time periods (Cooper *et al.,* 2008).

The Malmquist index technique allows a separation between the Catch-up effect and Technological Change, *i.e.,* the displacement of the best practices frontier over time due to technological progress (Gúzman & Reverte, 2008).

For a DMU, if the inputs and outputs (xt, yt) observed at $t = 1$ and $t = 2$ are $A_1 = (6, 2)$ and $A_2 = (4, 4)$, respectively, the relative efficiency levels are 0.067 for the first period (B_1/A_1) and 0.75 for the second (C_2/A_2). Thus, the DMU at $t = 2$ has improved its efficiency level with respect to the frontier. As shown in figure 6, the frontier has also moved in time. To measure this effect, it is necessary to move reference point B_1 to B_2 over the period 2 frontier. Then, the convergence to the frontier corresponding to A_1 is evaluated by $[(B_1/A_1) / (B_2/A_1)]$ and similarly for A. To compute the total innovation effect, we take a geometric average of both convergences (figure 8). Finally, the Malmquist Productivity Index is the result of multiplying the efficiency change effects by technological change (Ferro & Romero, 2011).

Figure 8. *The Malmquist Index Components*



Source: Ferro & Romero (2011).

The displacement of the TC frontier curve does not strictly refer to some innovation or technical development; the displacement can also occur due to other phenomena such as a greater use of installed capacity and/or an improvement in resource management, capacities, or knowledge within the sector. The construction of the Malmquist index involves defining the distance functions of two different time periods and calculating the technology variation for each observation through the geometric mean of the distances in both periods (Becerril-Torres *et al.*, 2011). A Malmquist index of less than 1 indicates a deterioration in TFP in two periods; a value greater than 1 indicates an improvement over the preceding period (Ferro & Romero, 2011).

IV. Methodological Approach for Productivity Measurement

This chapter is divided into two sections. The first part analyzes the theoretical and methodological aspects of DEA and the Malmquist index; these are models used to calculate efficiency and TFP change respectively for each of the 20 countries analyzed. In the second part, the empirical bases of the analysis are developed; this includes a literature review on DEA application to the oil and energy industries (they have similar inputs and outputs), a selection of variables, and all information sources for data collection.

Method and Methodology

In the literature of research methodology, several definitions have emerged over time in reference to the scientific method. Pérez (2003) establishes the following definition: "By scientific method I understand the sum of theoretical principles, rules of conduct, and mental and manual operations used in the past and still used today by scientists to generate new scientific knowledge" (42).

Scientific Method

The scientific method will be used in this research to provide a foundation and to fulfill the structural requirements accepted by the scientific community. The results and conclusions should be credited and contribute with new knowledge, quality, and a scientific character. There are several expressions of the scientific method, but two of them will stand out in this research work: the hypothetical-deductive and the analytical-deductive.

The research is hypothetical deductive because it presents initial principles or brief ideas trying to solve the research problem. As the work progresses, it integrates the results to conclude if the proposed hypotheses are fulfilled or not. It is also analytical deductive because the models first decompose the general concept into particularities to determine how they relate to each other; it identifies what their causes and effects are; and it finally reaches a full picture of the problem, concluding with a new, more general approach to Mexico's oil industry.

Methodology

Historical and statistical data will be collected on the variables relevant to this study. The information collected will be used to perform linear programming and to express the multi-input, multi-output production results for each country. The study provides an envelope analysis of the best DMU's using a deterministic non-parametric frontier model, known as DEA, to determine the technical efficiency of the upstream sector.

With the different frontiers obtained for all periods, the effects of efficiency and technological change on the DMU's' productivity change will be measured using the Malmquist index and change ratios. Finally, TFP will be calculated multiplying technical efficiency by technological change.

Instruments

An appropriate measurement instrument records observable data that truly represent the concepts or variables that the researcher has in mind. Measurement instruments are the tools used to carry out observations (Hernández Sampieri *et al.*, 2006).

Quantitative Instruments

A quantitative instrument uses data collection and analysis to answer research questions and to test previously established hypotheses; it relies on numerical measures, counting, and statistics to accurately establish behavior patterns in a population. It explains observed phenomena as objectively as possible, thus contributing to the generation of knowledge (Hernández *et al.*, 2006).

According to Navarro & Santillan (2007), there are two options regarding the use of measurement instruments in a research: *1)* to choose an already developed and available measurement instrument, which is adapted to the requirements of a particular study, and *2)* to construct a measurement instrument according to the appropriate technique for it.

The information that is already published will be collected for this research, and statistical and linear programming tools will be used to determine the necessary envelope for the DEA model. Such information will be collected from institutional databases like SENER and PEMEX. A request was made to the National Transparency System (SNT) through the Transparency Platform to obtain less aggregated data on production assets belonging to the subsidiary PE. Given the selected methodology, it is essential to collect disaggregated data for each petroleum extraction field on their exploration and production assets, their number of employees, proven reserves, and production.

Information from other countries is obtained by reviewing the WB database on petroleum production and reserves. In the case of EP's assets and number of employees, we obtained a database from organizations and institutions created for the control of operations in the oil industry such as OPEC, S&E, and IPA. Finally, we reviewed the operation reports of companies operating in countries that do not belong to specific organizations or do not report their activity, and such data were aggregated in a common database; these cases were Russia and China.

Universe and Sample

A population is determined by its defining characteristics; therefore, the set of elements with such characteristics is called population or universe. The population is the whole phenomenon under study; here, the population units present a common characteristic, which is studied giving rise to the research data (Bernal, 2000). The universe of this research will be integrated by all the decision-making units of the upstream sector in the world's oil industry, both for IOC's and NOC's.

On the other hand, a sample can be defined as a subset of a population, and it should be representative of that population (Salkind, 1999). The subjects of this research are the main oil producing countries and PEMEX PE as a subsidiary company; each country is considered as an independent DMU.

Table 7. *Top 20 Oil Producing Countries (DMU's)*

Ranking	*Country*
1	Russia
2	Saudi Arabia*
3	United States
4	Iraq*
5	Iran*
6	China
7	Canada
8	United Arab Emirates*
9	Kuwait*
10	Brazil
11	Venezuela *
12	Mexico
13	Nigeria *
14	Angola*
15	Norway
16	Kazakhstan
17	Qatar*
18	Algeria*
19	Oman
20	United Kingdom

Notes: * OPEC member countries. Qatar was a member of OPEC until January 2019.
Source: Authors' design based on WB data (2018).

Theoretical-Methodological Analysis of the DEA Technique and the Malmquist Index

This section comprises the theoretical aspects of data envelopment analysis and the Malmquist index as well as the methodological elements for their calculation.

DEA's theoretical and methodological attributes

In the second chapter the theoretical aspects of productivity and efficiency were described. The DEA technique is a methodology used for the comparative measurement of homogeneous units, *i.e.,* those having the same economic rationale (purpose). Starting from inputs and outputs, DEA provides an ordering of agents by giving them a relative efficiency score (Emid, 2011). Thus, the agents or DMU's with the highest output level and the least number of inputs are the most efficient of the group and will obtain the highest scores. It is a deterministic non-parametric frontier method; this means that production is evaluated based on productive functions that do not require any assumptions about the production frontier. The efficiency of any given unit is assessed based on the units with the best performance; this gives rise to the possibility of reviewing the benchmarking instead of just analyzing a behavior that tends towards the mean[1], as does the regression analysis (Arieu, 2006).

DEA models make use of the DMU's' know-how[2], thus identifying the efficient and inefficient ones. In addition, they set improvement targets for the latter based on the achievements of the former; benchmarking is performed using only the information available in the DMU's themselves without the need for theoretical assumptions (Delfín & Navarro, 2015).

The main advantage of these models is that they provide a global indicator of efficiency (or inefficiency); they are based on their theoretical basis

[1] When performing a parametric analysis, it is necessary to determine the mean of the sample to determine how far the rest of the observations depart from it; it is also important to define a standard error to perform regressions that separate the error terms from the parameters of the phenomenon. In non-parametric models, the distance to the observations with the best result is taken as a reference (Kendrick, 1961).

[2] Technical or organizational knowledge that certain people or companies have obtained through experience and that is necessary for the development of a specific activity (Lakshman, 2007).

without having to assign weights to the different outputs and inputs beforehand. Also, these models adapt to multi-product contexts, and inputs and outputs can be expressed indistinctly in monetary terms and/or physical units (Navarro & Torres, 2006a).

Among the disadvantages of the DEA technique are the difficulty in testing statistical hypotheses; results are susceptible to a poor specification of the associated input/output variables to be used; the number of observations compared must be the maximum possible. On the other hand, the units of analysis must be similar to each other (Becerril-Torres *et al.*, 2011).

In this sense, the definition used for efficiency is (Mercado *et al.*, 1997):

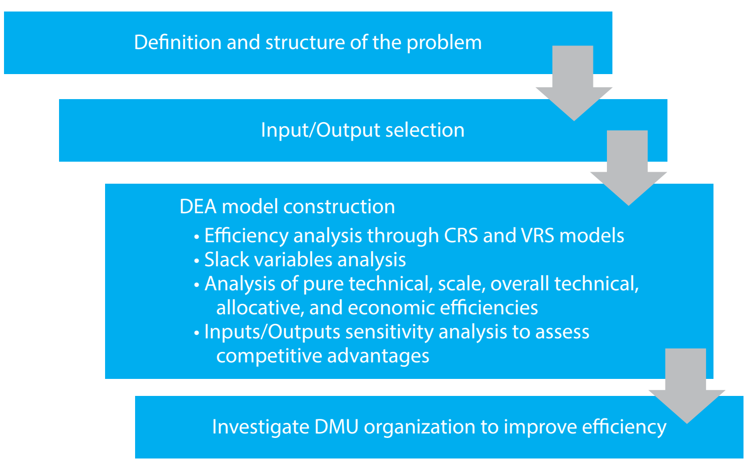
$$Efficiency = \frac{Total\ Outputs}{Total\ Inputs}$$

Or formally:

$$E = \frac{\sum_{i=0}^{N} v_i y_i}{\sum_{i=0}^{N} u_i x_i} \quad (1)$$

Where E represents efficiency, x_i and y_i are the inputs and outputs respectively, and parameters u_i and v_i show the relative importance of each parameter.

Figure 9. *DEA Methodology*



Source: Navarro & Torres (2006b).

From the methodological point of this research, these and other aspects lead to a DEA analysis of productivity and to alternative proposals to improve efficiency. This is shown in the figure.

DEA Models with Constant Returns to Scale (CRS)

The first proposal by Charnes, Cooper, and Rhodes (1978) is based on the ratio model. Here, the weights assigned by the different outputs and inputs are not fixed *a priori* but are determined by a linear program. This model is appropriate when all firms operate on an optimal scale. However, imperfect competition, government regulations, and financial constraints may cause a firm not to operate at the optimal scale. Its mathematical formulation is as follows:

$$\max \frac{\sum_{r=1}^{m} u_r y_{r0}}{\sum_{i=1}^{n} v_i x_{i0}}$$

s.a.

$$\frac{\sum_{r=1}^{m} u_r y_{rj}}{\sum_{i=1}^{n} v_i x_{ij}} \leq 1;\ j = 1, \ldots, 0, \ldots, I$$

$$u_r, v_i \geq 0;\ r = 1, \ldots, m; i = 1, \ldots, n \qquad (2)$$

Where y_{rj} is output r of DMU j; x_{ij} is input i of DMU j; u_r is the weight assigned to output r, and v_i is the weight of input i. This linear program is solved for each of the units analyzed.

The efficiency of a DMU is defined as the ratio between the weighted sum of its outputs and the weighted sum of its inputs. These weights, however, are left free to maximize the unit's efficiency; under this assumption, its performance is compared to the rest of the DMU's (Becerril-Torres *et al.*, 2011). The restrictions force the DMU's efficiency ratios to be equal to or less than 1; the purpose of this is to achieve normalization in the efficiency measure. Thus, if the ratios are equal to 1, they will represent the DMU's Overall Technical Efficiency (OTE); if they are less than 1, they will indicate a respective level of inefficiency.

As it can be seen, the previous expression is not linear, which makes it difficult to be solved numerically. To solve this problem, we proceed to its linearization by means of the following transformation.

$$\max \sum_{r=1}^{m} u_r y_{r0}$$

$$\textbf{\textit{s.a.}}$$

$$\sum_{i=1}^{n} v_i x_{i0} = 1$$

$$\sum_{r=1}^{m} u_r y_{rj} \leq \sum_{i=1}^{n} v_i x_{ij} \;\; j = 1, \ldots, 0, \ldots, I$$

$$u_r, v_i \geq 0; \; r = 1, \ldots, m; \; i = 1, \ldots, n \tag{3}$$

The described formulation of the CRS model is often referred to as the CRS ratio form, although it is more common to use its dual program:

$$\min \theta$$

$$\textbf{\textit{s.a.}}$$

$$\left(\sum_{i=1}^{n} \lambda_j y_{rj}\right) - s_r^+ = Y_{r0} \; r = 1, \ldots, m$$

$$\left(\sum_{j=1}^{I} \lambda_j x_{ij}\right) - s_i^- = \theta x_{i0} \; i = 1, \ldots, n$$

$$\lambda_j, s_r^+, s_i^- \geq 0; \; \theta \textit{ free of sign} \tag{4}$$

Because of the generally accepted characteristics of production technologies, θ cannot take a negative value since positive outputs cannot be obtained from a vector of negative inputs or free production. As it is the target function of minimization, the smallest value will be obtained so that θ meets all restrictions. In fact, the aim is to find a linear combination of DMU's (or reference unit) that achieves an output greater than or equal to that of the DMU analyzed and an equal or lower input consumption. This implies that if such a linear combination cannot be found, the same DMU under analysis will be obtained as a reference, so it will take 1 as a maximum value; therefore, $\theta \in (0, 1]$ (Giménez, 2004).

θ provides the ETG index of the DMU under analysis. Its interpretation is the maximum level at which the consumption of all inputs could be reduced without changing their mix. For this reason, the formulation of the problem is input-oriented and is a radial model *(idem)*.

However, additional decreases in some inputs can be achieved by admitting changes in the input-mix. The targets set for the inputs under this assumption would be given by the following expression, where superscripts "*" denote the optimal value of the variables:

$$\theta^* x_{i0} - s_i^{-*}$$

The target for output r should be set to: $y_{r0} + s_r^{+*}$.

In parallel, the output-oriented CRS model can be considered as follows:

$$\max \phi$$

$$\boldsymbol{s.a.}$$

$$\left(\sum_{j=1}^{I} \lambda_j y_{rj}\right) - s_r^+ = \phi Y_{r0} \; r = 1, \ldots, m$$

$$\left(\sum_{j=1}^{I} \lambda_j x_{ij}\right) - s_i^- = x_{i0} \; i = 1, \ldots, n$$

$$\lambda_j, s_r^+, s_i^- \geq 0; \; \phi \; \textit{free of sign} \tag{5}$$

As in the previous case, ϕ will not take negative values due to the characteristics of the production technology; it is not possible to obtain positive outputs from a negative vector of inputs or from free production. As it is the target function of maximization, the highest value will be obtained so that ϕ meets all restrictions. The aim is to find a linear combination of DMU's that achieves an output greater than or equal to that of the DMU analyzed and an equal or lower input consumption.

This means that if such a linear combination cannot be found, the same DMU under analysis will be obtained as the reference, so it will be equal to; therefore, $\phi \in [1, +\infty)$.

In this case, ϕ should be interpreted as the increase that, as a percentage of one, could be achieved in all outputs with changing their mix. Thus, if a DMU can radially expand all its outputs, it will obtain $\phi > 1$; otherwise, $\phi = 1$. Therefore, this case is also a radial model.

As in the input-oriented model, additional increases in some output can be achieved, admitting changes in the output-mix as a counterpart. In this case, the target set for the r output should be given by the following expression:

$$\phi^* y_{r0} + s_r^{+*}$$

Whereas the target for input i should be set as follows:

$$x_{i0} - s_i^{-*}$$

The extraction of crude oil as a primary resource depends on the infrastructure necessary for the discovery and evaluation of deposits, their development, and final extraction of hydrocarbons. Thus, the model selected for this research is output-oriented; certain technology levels (mix-inputs) are compared to determine where the greatest amount of output is achieved (Delfín & Navarro, 2014).

DEA Models with Variable Returns to Scale (VRS)

Basic DEA models consider constant returns to scale and variable returns to scale. In models with constant returns to scale, the units take a referential DMU: the one with the highest productivity when calculating their relative efficiency. On the other hand, models with variable returns to scale require to introduce a restriction based on linearized ratio models or a variable indicating that each DMU must be compared with those of the same size and not with all the units present in the program (Banker *et al.,* 1984). By changing the enveloping form of the CRS-INPUT model into:

$$\min \theta_0$$

$$\textbf{\textit{s.a.}}$$

$$\left(\sum_{j=1}^{I} \lambda_j y_{rj}\right) - s_r^+ = y_{r0} \; r = 1, \ldots, m$$

$$\left(\sum_{j=1}^{I} \lambda_j x_{ij}\right) - s_r^- = \theta x_{i0} \; i = 1, \ldots, m$$

$$\sum_{j=1}^{I} \lambda_j = 1$$

$$\lambda_j, s_r^+, s_i^- \geq 0; \; \phi \textit{ free of sign} \qquad (6)$$

it can be observed that the additional restriction in the model's dual, the sum of components in vector ($\lambda_1, \lambda_2, \ldots, \lambda_n$) is equal to 1, forces the DMU projection to be made on the hyperplane formed by the most productive units of the same size. In this case, the units that were not efficient in the previous CRS model but are efficient in this model will show up. Hence, the technical efficient frontier is formed by more observed units than in the CRS-INPUT model (Villa, 2003).

The relative efficiency of each unit is ϕ_0. The same considerations observed in the CRS model concerning the projections of the frontier and the values of the slack variables are still valid in this model. It is different from the input-oriented problem because the radial reduction is only allowed for inputs *(idem).*

The model is invariant in terms of output conversions since there are no radial amplifications for them, and it is invariant in terms of the measurement units for the inputs. On the other hand, if the problem is output-oriented, we would obtain a model analogous to the previous one *(idem).*

The mathematical formulation for the output-oriented case is as follows:

$$\max \phi$$

$$\textit{\textbf{s.a.}}$$

$$\left(\sum_{j=1}^{I} \lambda_j y_{rj}\right) - s_r^{+} = \phi y_{r0} \; r = 1, \ldots, m$$

$$\left(\sum_{j=1}^{I} \lambda_j x_{ij}\right) - s_r^{-} = x_{i0} \; i = 1, \ldots, m$$

$$\lambda_j, s_r^{+}, s_i^{-} \geq 0; \; \phi \; \textit{free of sign} \tag{7}$$

The implementation of restriction $\sum_{j=1}^{I} \lambda_j = 1$ reduces the CRS assumption and moves on to the VRS assumption (Becerril-Torres *et al.*, 2011). This restriction makes the reference unit to be a convex linear combination of others; so, if DMU's of similar sizes are compared, the rest of the linear program restrictions must be met.

There is also the possibility of including restriction $\sum_{j=1}^{I} \lambda_j \leq 1$, but this would require a technology with non-increasing returns to scale.

DEA Models with Scale Inefficiencies (NIR)

The programs designed by Charnes, Cooper, and Rhodes (1978) calculate the efficiency index under the constant return's assumption. Banker, Charnes, and Cooper (1984) later relaxed the restriction by including a technology with variable returns to scale. Färe, Grosskopf, and Lovell (1994) showed how the sources of scale inefficiencies can be estimated.

Scale inefficiencies are used to determine how close a firm is to the most productive scale (Banker *et al.,* 1984); this is a type of inefficiency related to the DMU size. Once the scale inefficiencies have been detected, we compare the new index calculated under the assumption of variable returns with another index calculated under the returns that generate them.

This new index can be formulated by changing the additional restriction on the intensity vector to one that imposes non-increasing returns to scale; then the sum of its elements should be less than or equal to 1. This way, the nature of scale inefficiencies in a particular DMU can be determined by comparing the degree of technical efficiency in non-increasing returns with the degree of technical efficiency in variable returns *(idem).*

If these values are different, the DMU has increasing returns to scale; if they are equal, the DMU has decreasing returns, *i.e.,* the firm shows scale inefficiency *(idem).* Restriction for NIR:

$$\sum_{j=1}^{I} \lambda_j \leq 1$$

Banker and Morey (1986a and 1986b) thought that certain input quantities could not be adjusted in the short run. Färe, Grosskopf and Lovell (1994), and Coelli *et al.* (1998), differentiate between fixed and variable inputs, which are incorporated in the program allowing the adjustment of variable inputs *(vx)* while maintaining the level of fixed inputs *(fx).* This change can be extended to other returns to scale by incorporating the restrictions on the intensity vector.

Slack Analysis of Variables

A radial reduction of the vector of controllable factors may not be enough to achieve efficiency; it may be necessary to further reduce a factor or increase an output, which can be determined through the values of slack variables (Murias *et al.,* 2008).

A slack analysis of variables in DEA models sets the guidelines for DMU's to improve their efficiency levels. Thus, the output slack value represents the additional level of output necessary to convert an inefficient DMU into an efficient one (Navarro & Torres, 2006b). Therefore, an input slack value represents the input reductions necessary to convert a DMU into an efficient one (Lo *et al.,* 2001).

Benchmarking

Benchmarking is defined as comparing a firm's performance with that of best-in-class companies. It determines how the best of them have achieved their performance levels: the information is used as a basis to set a company's own goals, strategies, and procedures (Bemowski, 1991). The process of benchmarking:

- Determine the correct characteristics of the receiving process and use them to compare one process with another (donor).
- Develop data on the best practices inside or outside an organization that requires benchmarking.
- Compare and evaluate process(es) according to data on the evaluated features.
- Develop measures for continuous improvement based on new data.
- Implement planned process changes.
- Monitor the effectiveness of such changes.

According to Delfín & Navarro (2014), benchmarking requires a planned evaluation and implementation action. It is an attempt to modify a process in the light of new knowledge about a more efficient behavior. Benchmarking is divided into three areas:

- *Internal.* An evaluation of practices within an organization.
- *Competitive.* Very limited in actual practice as it requires competitors to admit and cooperate in the improvement of one or both organizations.
- *Inter-industry.* Evaluations between operations in different industries.

Benchmarking means adapting best practices rather than copying them. It involves using knowledge to determine what is useful from the donor's process. Thus, the mentality or culture surrounding benchmarking is to improve and exceed the performance dimensions of the donor's process (Navarro, 2005).

Bootstrap

Estimates obtained by DEA may be biased and affected by the uncertainty derived from sampling variations (Ceccobelli *et al.*, 2012). In addition, efficiency results using DEA are relative as the true production frontier is unknown (Simar and Wilson, 2010). Since the estimates are point estimates, DEA results also lack the statistical properties needed to make inferences (Simar and Wilson, 2000). This is because the frontier model calculates efficiency non-parametrically and assumes that there is no functional form (Simar and Wilson, 2007).

DEA estimates are deterministic and do not consider the measurement of statistical error. In their original form, these efficiency estimates are invalid for making conventional statistical inferences; it is unknown whether relationships and dependencies exist between efficiency estimates (Hawdon, 2003). The solution to these problems is the use of the Bootstrap technique in DEA. In its basic form, the Bootstrap algorithm involves an intensive process of computing synthetic samples by randomly selecting replacement samples from an observed sample. The goal is to obtain statistical properties for efficiency results; the main principle is to approximate a sample distribution towards the true efficiency values by generating data. Using the standard error or through hypothesis testing, it is possible to assess how close the new sample is to the original sample of the universe. Simar & Wilson (2007) recommend the use of 2000 samples generated by Bootstrap.

Measuring Productivity through the Malmquist Index

The Malmquist Index is a method based on frontier functions that differentiates between movements towards and movements across the frontier. It measures how close a level of production is to the level of technical efficiency, given a set of production factors, *i.e.,* how close a production vector is to the frontier, given a vector of factors (Färe *et al.,* 1994).

The construction of the Malmquist Index entails determining the distance functions in two different time periods and calculating the technological change for each observation in the geometric mean of distances for both periods. The input distance function is defined as the maximum reduction of inputs keeping a constant level of output within a set of production possibilities *S* for a reference period *t;* this is mathematically expressed as (Becerril-Torres *et al.*, 2011; Delfín & Navarro, 2015):

$$D_i^t(x^t, y^t) = \{\inf[\theta : (\theta x^t, y^t) \in S^t]\}^{-1} = \{\sup[\theta : (x^t/\theta, y^t) \in S^t]\}^{-1} \quad (8)$$

Where x is the vector of inputs, y is the vector of outputs, and θ is a scalar that measures the proportional reduction in all inputs while maintaining the same level of output. The construction of the Malmquist index entails determining the distance functions in two different time periods, in which the advance in productivity is measured; one period is defined by the observation, and another is defined by the reference period of technology (Färe *et al.,* 1994); it is as follows:

$$D_i^t(x^{t+1}, y^{t+1}) = \{\inf[\theta : (\theta x^{t+1}, y^{t+1}) \in S^t]\}^{-1} \quad (9)$$

Distance function $D_i^t(x^{t+1}, y^{t+1})$ measures the maximum reduction of inputs to make (x^{t+1}, y^{t+1}) possible in technology period t. Similarly, the distance function of observation can be defined in period $(t + 1)$.

$$D_i^{t+1}(x^t, y^t) = \{\inf[\theta : (\theta x^t, y^t) \in S^{t+1}]\}^{-1} \quad (10)$$

Färe *et al.* (1994) define the Malmquist productivity index taking technology as a reference in the geometric mean and decomposing the index as follows:

$$M_i(x^{t+1}, y^{t+1} x^t, y^t) = \frac{D_i^{t+1}(x^{t+1}, y^{t+1})}{D_i^t(x^t, y^t)} \times \frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^{t+1}(x^t, y^t)} \times \left[\frac{D_i^t(x^t, y^t)}{D_i^{t+1}(x^t, y^t)}\right]^{\frac{1}{2}} \quad (11)$$

The quotient between brackets is the geometric mean of two quotients reflecting movements in the technology frontier between the two periods y and $t + 1$. This indicates technological change: if it adopts a value > 1, technological progress occurred; if the value is < 1, a technological regression took place; and if it is $= 1$, the technology has remained constant (Delfín & Navarro, 2015).

The ratio outside the brackets reflects the change in relative efficiency; it is measured as the quotient of efficiencies between the periods considered in the analysis. In this scenario, if the ratio is >1, it shows an improvement in relative efficiency in period t to $t + 1$; if it is < 1, relative efficiency has decreased; and if it is = 1, relative efficiency has remained the same *(idem).*

To calculate the Malmquist index, Farë *et al.* (1994) use the CRS. In addition, they propose an OTE change; this can decompose the PTE change, which is exclusively represented by the technical management of the DMU regardless its size. They also propose an SE change derived from the size of the productive unit in relation to the optimal scale. This decomposition is obtained by incorporating the assumption of a technology with variable returns to scale as follows:

$$ETG_i^{t+1} = \frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^t(x^t, y^t)} = \left\{ \frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^{t+1}(x^t, y^t)} \right\}_{VRS} \left\{ \frac{\dfrac{[D_i^{t+1}(x^{t+1}, y^{t+1})]_{CRS}}{[D_i^{t+1}(x^{t+1}, y^{t+1})]_{VRS}}}{\dfrac{[D_i^{t+1}(x^t, y^t)]_{CRS}}{[D_i^{t+1}(x^t, y^t)]_{VRS}}} \right\} = ETP_i^{t+1} \times EE_i^{t+1} \tag{12}$$

The Malmquist index has two variants, and its estimation requires calculating the distance functions according to the orientation. Färe, Grosskopf, and Lovell (1994) propose a way to solve such a situation using DEA mathematical programming; here, the distance function of the DMU in periods t and $t + 1$ requires solving four linear programming problems: $D_i^t(x^t, y^t)$, $D_i^{t+1}(x^t, y^t)$, $D_i^t(x^{t+1}, y^{t+1})$, and $D_i^{t+1}(x^{t+1}, y^{t+1})$. Here, the output distance function is reciprocal to Farrell's (1957) output-oriented measure of technical efficiency.

$$\begin{aligned} [D_i^t(x^{k't}, y^{k't})]^{-1} &= \max \theta^{k'} \\ \text{s.a.} \sum_{k=1}^{k} \lambda^{k,t} y_m^{k,t} &\geq \theta^{k'} y_m^{k,t} m = 1, \ldots, M \\ \sum_{k=1}^{k} \lambda^{k,t} x_m^{k,t} &\geq \theta^{k'} x_m^{k,t} n = 1, \ldots, M \\ \lambda^{k,t} &\geq 0k = 1, \ldots, K \end{aligned} \tag{13}$$

Where x and y represent respectively the inputs and outputs of the DMU's production process. k' represents 1, 2, ..., k DMU's, using n = 1, 2,

..., N inputs $\lambda_m^{k,t}$, at each time period $t = 1, 2, ..., T$. These inputs are used to produce $m = 1, 2, ..., M$ outputs $y_m^{k,t}$ (Delfín & Navarro, 2015).

To calculate the distance function with respect to period $t + 1$, a similar mathematical expression is used in which a superscript t is replaced with $t + 1$ in the equations presented above. As for the distance function $D_i^t(x^{t+1}, y^{t+1})$ it is estimated by substituting superscript t for $t + 1$. Likewise, the estimation of function $D_i^t(x^t, y^t)$ is specified by replacing superscript t with $t + 1$.

The Malmquist index allows the decomposition of productive change into technical efficiency improvements and into technological change. It also allows describing a technology with multiple inputs and outputs without the need to specify a behavioral objective, such as cost minimization or profit maximization (Coelli *et al.*, 1998).

Case Study and Development for Variable Selection

The following bibliographic review was carried out for a correct analysis of the research problem, an adequate choice of variables, theoretical support, and application of the methodological tools.

Table 8. *Bibliographic Review*

Year	*Author*	*Title*
2000	Sueyoshi	Stochastic DEA for Restructure Strategy: An Application to a Japanese Petroleum Company
2001	Cudington & Moss	Technological Change, Depletion, and the U.S. Petroleum Industry
2005	Navarro, J.	La eficiencia del sector eléctrico en México
2006	Abbott, M.	The Productivity and Efficiency of the Australian
2006	Abdullah *et al.*	Efficiency Diferences between Private and State-owned Enterprises in the International Petroleum Industry
2007	Wang *et al.*	Performance based Regulation of the Supply Industry in Hong Kong: An Empirical Efficiency Analysis Approach
2008	Vaninsky, A.	Environmental Efficiency of Electric Power Industry of the United States: A Data Envelopment Analysis Approach
2009	Torres, Ayuso & Laura	Disparidades en eficiencia técnica y convergencia en eficiencia en México: un análisis de frontera
2010	Eller *et al.*	Empirical Evidence on the Operational Efficiency of National Oil Companies

Year	*Author*	*Title*
2011	Peter R. Hartley, Kenneth B. Medlock	La eficiencia de ingresos de PEMEX: un enfoque comparativo
2012	Sueyoshi & Goto	Data Envelopment Analysis for Enviromental Assessment: Comparizon between Public and Private Ownership in Petroleum Industry
2012	Aparecida *et al.*	Efficiency in Brazilian Refineries Under Different DEA Technologies
2017	Guevara *et al.*	The Status an Evolution of Energy Supply and Use in Mexico Prior to the 2014 Energy Reform: An Input-Output Approach
2017	Ohene-Asare *et al.*	Multinational Operation, Ownership and Efficiency Differences in the International Oil Industry
2018	Sueyoshi & Wang	DEA Environmental Assesment on US Petroleum Industry: Non-radial Approach with Translation Invariance in Time Horizon

Source: Authors' design (2019).

Selection of DMU's

Exploration and production activities are carried out in the upstream sector of the oil industry by different countries in different continents. However, the number of proven reserves and the production of oil derivatives present important differences among countries. These contrasts exist even within the top 20 oil producing countries listed in this research, which concentrate more than 80% of oil reserves and crude oil production worldwide. The sample was reduced to five countries due to the difficulty in collecting data; governments or companies involved do not provide free access to reports and/or indicative statistical information. The selected countries are the following.

Table 9. *Production and Proved Reserves of the Upstream Sector 2017*

Countries	*Oil Reserves MMB*	*Ratio*	*Oil Production mBD*	*Ratio*
USA	49.97	2.95%	13 056.99	14.09%
Canada	168.92	9.96%	4 830.63	5.21%
Mexico	7.22	0.43%	2 224.15	2.40%
Brazil	12.79	0.75%	2 733.99	2.95%
Venezuela	303.18	17.87%	2 110.20	2.28%
Norway	7.92	0.47%	1 968.87	2.13%
UK	2.31	0.14%	999.13	1.08%
Russia	106.19	6.26%	11 257.26	12.15%
Iran	157.20	9.27%	4 981.68	5.38%
Iraq	148.77	8.77%	4 519.96	4.88%

Countries	*Oil Reserves MMB*	*Ratio*	*Oil Production mBD*	*Ratio*
Kuwait	101.50	5.98%	3 025.44	3.27%
Saudi Arabia	266.21	15.69%	11 950.27	12.90%
UAE	97.80	5.76%	3 935.27	4.25%
Angola	9.52	0.56%	1 674.39	1.81%
Nigeria	37.45	2.21%	1 987.75	2.15%
China	25.66	1.51%	3 845.94	4.15%
Subtotal	1 502.61	88.57%	75 102.51	81.06%
Rest of the World	193.99	11.43%	17 546.12	18.94%
Total	**1 696.60**	**100.00%**	**92 648.63**	**100.00%**

Source: Authors' design based on WB (2018).

Table 7 shows the relevance of the main oil producing countries worldwide; they covered about 89% of oil reserves and 81% of global production in 2017. The sample selected for this research is significant because it includes these countries in the efficiency and TFP analysis, only excluding Iraq.

Norman and Stoker (1991) suggest that the minimum number of DMU's to be analyzed should be 20, while Banker *et al.* (1984) propose that inputs plus outputs ≤ 0.3 * DMU's. In their work, Lo *et al.* (2001) propose that the number of DMU's should be at least twice the sum of inputs plus outputs.

Based on these parameters, the minimum number of DMU's necessary to perform the DEA analysis for three inputs and two outputs must be between 20 and 10. So, 15 DMU's is enough as proposed by Banker *et al.* (1984) and Lo *et al.* (2001).

Variable Selection

According to the theory and methodology, the independent variables selected for this study are divided into inputs and outputs. Each variable is fed with data from the *upstream* sector of the global oil industry. Following the guidelines of the DEA model and for the Malmquist index, the data are presented in physical units (to obtain levels of technical efficiency); they are discrete and deterministic in nature as they reflect the direct value observed in practice. The data were collected for each period analyzed.

In table 10, the variables with the highest frequency are number of employees, capital expenditures, petroleum barrels, petroleum production wells, exploration wells, petroleum reserves, and gross capital formation. After a literature review and considering that both NOC's and IOC's will be analyzed, it is essential to include those variables that are homogeneous in their process.

The main difference between state-owned and privately owned companies is their financial goal; the former focus on the social burden and contribution to public spending, the latter focus on the delivery of profits to their owners (Nahar, 2006). This research focuses on the number of employees, exploration wells, extraction wells, petroleum reserves, and petroleum production; these variables are homogeneous for both types of companies.

Table 10. *Frequency of Variables*

Variable	*Sueyoshi (2000)*	*Cudington & Moss (2001)*	*Abbott (2006)*	*Nahar (2006)*	*Torres et al. (2009)*	*Wang et al. (2007)*	*Vaninsky (2008)*	*Eller et al. (2010)*	*Hartley et al. (2011)*	*Sueyoshi (2012)*	*Aparecida (2012)*	*Guevara et al. (2017)*	*Ohene-Asare (2017)*	*Sueyoshi et al. (2018)*	*Total*
Employees	*		*	*	*			*		*			*		7
Gas Station Size	*														1
COPEX	*	*							*	*					4
Petrol	*											*			2
Oil Barrels	*						*		*	*	*	*	*	*	8
Production Wells		*					*		*	*					4
Exploration Wells	*	*								*				*	4
Oil Reserves		*						*		*			*		4
Gas Reserves		*								*			*		3
Backlog of Reserves		*													1
Gross Capital Formation			*	*	*				*						4
Energy Used			*									*		*	3
Power Consumption			*									*			2
Capital Productivity				*											1
Labour Productivity				*		*		*							3
GDP					*										1
Laboral OPEX						*									1
No. of Clients						*									1
CO_2 Emissions							*			*	*				3
Energy Losses							*								1
Oil Reserves Used								*							1
Profits									*						1
Gas Production										*			*		2
Years in Operation											*				1
Processed Oil											*				1
Population														*	1

Source: Authors' own design (2020).

Inputs:

- *Exploration wells (EW).* Number of active wells for exploration of new fields; they are aimed at recovering oil reserves and categorizing the viability and size of oil fields.
- *Extraction/production wells (PW).* Number of active hydrocarbon extraction wells (essentially crude oil) of any type (onshore, shallow water, platform); their function is to extract hydrocarbons from discovered fields that can be exploited.
- *Labor force (LF).* Number of manual, administrative, and temporary workers employed in the exploration and production phase (upstream sector) of the oil industry in each country under study.

Outputs:

- *Proven petroleum reserves (PR).* Millions of petroleum barrels discovered in the oilfields. The oilfield size and the viability of hydrocarbon extraction are evaluated in each country analyzed. The recovery of reserves is taken into account in this research; it is the reserves produced during the year of study, unlike other studies that take into account the accumulated reserves reported by the countries at the end of the year.
- *Total crude oil production (TP).* Crude oil Barrels extracted by each country; the total produced at the end of the year is observed in this research.

Pearson's Correlation and Factor Analysis

After reviewing the literature and analyzing the upstream sector operations, we conducted a factor analysis to support the selection of variables.

Factor analysis is a data reduction technique used to find homogeneous groups of variables from a set of variables. The purpose of this analysis is to find the minimum number of dimensions capable of finding the maximum amount of information contained in the data. It is responsible for analyzing the common variance of all variables, starting from a correlation matrix (Carmona, 2014).

A sample adequacy test known as Kaiser-Meyer-Olkin (KMO) is also performed. It is used to counterbalance the magnitudes of partial correlation coefficients, the smaller its value, the higher the value of the partial correlation coefficients. Consequently, it is less appropriate to perform a factor analysis because the correlations are not explained by other variables *(idem)*.

Barlett's test of sphericity was performed; it determines the applicability of the factor analysis in the variables studied. The model is significant (the null hypothesis is accepted) when the factor analysis can be applied, provided that the significance is less than 0.05 (Carmona, 2014).

As can be seen in Table 11, the correlation of two inputs with respect to the outputs is greater than 0.5, which indicates that it is positively correlated. The LF input shows a lower relationship with the total production but higher than 0.5 with the proven oil reserves. On the other hand, EW show a correlation of 0.534 with reserves but only 0.420 with the total production, which shows the nature of the upstream sector operations.

Table 11. *Pearson Correlation*

		EW	*PW*	*LF*	*PR*	*TP*
Correlation	EW	1.000	.926	.464	.534	.420
	PW	.926**	1.000	.386*	.611*	.625*
	LF	.464*	.386*	1.000	.633*	.294*
	PR	.534*	.611*	.633*	1.000	.706**
	TP	.420*	.625*	.294	.706*	1.000
Sig. (one-sided)	EW		.000	.041	.020	.059
	PW	.000		.077	.008	.006
	LF	.041	.077		.006	.143
	PR	.020	.008	.006		.002
	TP	.059	.006	.143	.002	

** The correlation is significant at the 0.01 level (two-tailed).
* The correlation is significant at the 0.05 level (two-tailed).
Source: Authors' own design (2019).

The KMO test is used to assess the quality of the sample to be analyzed through factor analysis; Barlett's test of sphericity has the same purpose. In this case, the KMO statistic is 0.64 and the value of Bartlett's test is 0.000; so, it is considered appropriate to continue with the factor analysis.

Table 12. *KMO Test and Barlett's Sphericity*

Kaiser-Meyer-Olkin measure of sampling adequacy		.604
Bartlett's Sphericity Test	Approx. Chi-square	50.152
	df	10
	Sig.	.000

Source: Authors' own design (2019).

The communality of a variable is the proportion of its variance explained by the model. Through the communalities, it can be inferred that the variables with low values are those explained to a lesser extent by the model (Zamora & González, 2019). In this case, the variable that is explained to a lesser extent is LF; the rest have higher values, so they are explained in a better way as can be seen in the table below.

Table 13. *Communalities*

	Initial	*Extraction*
EW	1.000	.712
PW	1.000	.805
LF	1.000	.440
PR	1.000	.740
TP	1.000	.573

Source: Authors' design (2019).

The total variance explained was also obtained by means of a matrix; it showed the eigenvalues and variance percentage represented by each variable. The eigenvalues reflect the amount of total variance explained by each component, and the percentages of explained variance are obtained by dividing each eigenvalue by the sum of all of them. So, the result are components with eigenvalues greater than 1 (Zamora & González, 2019). In this case, we have an eigenvalue greater than 1; the result is a factor that explains the variance of the original data at 81.257%.

Table 14. *Total Variance Explained*

Component	*Initial Auto-Values*			*Sums of Squared Load Extraction*		
	Total	*Variance %*	*Cumulative %*	*Total*	*Variance %*	*Cumulative %*
1	3.270	65.398	65.398	3.270	65.398	65.398
2	.793	15.859	81.257	5.761	81.257	81.257
3	.713	14.262	95.519			
4	.187	3.744	99.262			
5	.037	.738	100.000			

Extraction method: main component analysis.
Source: Authors' own design (2019).

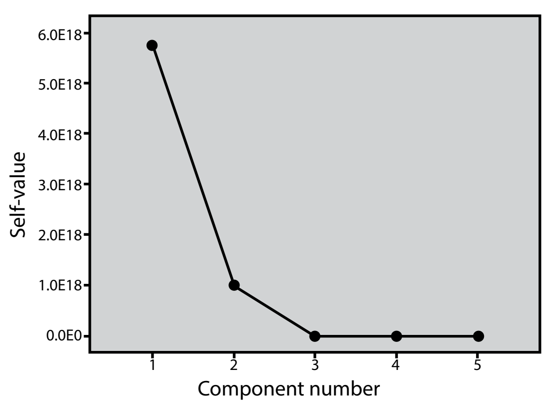
To explain 100% of the total variance, all components must be extracted; however, the components matrix only shows one component (see table 15).

Table 15. *Components Matrix*

	Component 1
PW	.897
PR	.860
EW	.844
TP	.757
LF	.663

Extraction method: main component analysis.
Source: Authors' design (2019).

Graph 8. *Sedimentation Graph*



Extraction method: main component analysis.
Source: Authors' design (2019).

Statistical Bases

The data were obtained mainly from the World Bank database, PEMEX's institutional database, and the Energy Information System of the Ministry of Energy. Reports from the Securities Stock and Exchange, the American Petroleum Industry, the Canadian Petroleum Association's Statistical Handbook, OPEC's Annual Statistical Bulletin, and British Petroleum Industry's Annual Statistical Report were reviewed as well.

V. Efficiency and Total Factor Productivity in the Upstream Sector

This chapter presents the results for technical efficiency levels of the 16 oil-producing countries studied through their upstream sector. The methodological guidelines of non-parametric DEA models with output orientation and variable returns to scale are considered. The results of each analyzed period will be presented in a static way; then a dynamic analysis is carried out through the Malmquist index to know the technical efficiency and technological changes as well as the way they affected their TFP.

Overall Technical Efficiency Based on the DEA-CRS Model

In the second section of the third chapter, we describe the Banker's model (1984) of constant returns to scale to calculate the OTE. The concept of OTE includes the effect of DMU size and considers the result obtained by the inputs used in the productive process. Navarro (2005) points out that a VRS analysis is necessary to consider market imperfections and the production process; however, this approach is also useful to create an overview of the sample under analysis.

Table 16 shows the results obtained through Banker's model (1984). The country with the best OTE performance is Saudi Arabia; it maintains an efficient operation (= 1) since 2008 and has the highest average of the sample. The following countries are Russia (0.9936), Kuwait (0.9667), Nigeria

(0.9559), Angola (0.9351), and Iran (0.8906). The countries with the worst OTE average are Canada (0.2654), USA (0.2767), China (0.2963), Mexico (0.4499), and Venezuela (0.4639).

In this vein, we observe two circumstances; OPEC countries have better performance: six out of seven countries included in the sample are in the top positions, being Saudi Arabia the best referent and Russia in second place. Venezuela is the lowest-ranked OPEC member, only below Brazil when considering the American countries.

Second: The American countries are grouped in the lowest level of OTE; in fact, the North American countries —Canada, USA, and Mexico— have the lowest results in the continent. Brazil is the American country with the best score (0.5916921), which is barely in the median of the overall results.

The year with the best average among the selected countries in the sample is 2015 (0.7308), which concurs with the only year in which Mexico obtained an OTE of 1. The lowest average of the upstream sector is 2008 (0.6172), the first year presented in this research. The general trend is upward with two downward peaks during 2015 and the 2016-2017 period, which keeps a slight drop in the overall average.

Table 16. *OTE CRS of the Upstream Sector in the Oil Industry, 2008-2017*

DMU	*Periodo*										*Promedio DMU*
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	
SAUDI ARABIA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
RUSSIA	0.9357	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9936
KUWAIT	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.6666	1.0000	1.0000	0.9667
NIGERIA	0.6590	0.9009	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9560
ANGOLA	1.0000	1.0000	1.0000	0.8706	0.7798	0.8293	0.8713	1.0000	1.0000	1.0000	0.9351
IRAN	1.0000	1.0000	1.0000	1.0000	1.0000	0.8903	0.8725	0.9174	0.7420	0.4841	0.8906
NORWAY	0.6801	0.5559	0.6396	1.0000	0.7520	1.0000	1.0000	0.8762	1.0000	0.4152	0.7919
UAE	0.7418	0.5860	0.9297	1.0000	1.0000	0.9183	1.0000	0.6196	0.3065	0.2573	0.7359
BRAZIL	0.2379	0.2013	0.2034	0.3431	0.3587	0.8776	0.9115	1.0000	1.0000	0.7835	0.5917
UK	0.2683	0.2843	0.3848	0.5654	0.5045	0.6477	0.4617	0.8141	0.8156	0.7457	0.5492
VENEZUELA	1.0000	1.0000	1.0000	0.3419	0.2142	0.2388	0.3396	0.1903	0.1558	0.1587	0.4639
MEXICO	0.2755	0.2644	0.3022	0.2621	0.2838	0.3526	0.4310	1.0000	0.5738	0.7540	0.4500
CHINA	0.2880	0.2337	0.3926	0.2954	0.3539	0.2907	0.3897	0.2776	0.1570	0.2845	0.2963
USA	0.0872	0.1613	0.1796	0.4021	0.1692	0.4551	0.3483	0.2851	0.3278	0.3512	0.2767
CANADA	0.0843	0.1230	0.1293	0.1448	0.1840	0.2301	0.2621	0.3161	0.3166	0.8644	0.2655
AVERAGE AN.	0.6172	0.6207	0.6774	0.6817	0.6400	0.7154	0.7258	0.7309	0.6930	0.6732	

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

The lowest efficiency levels are presented by Canada and the USA during 2008, with 0.0843 and 0.0872 respectively. Canada had its best performance in 2018 with 0.8644, and it is the only year in which it obtained a score higher than 0.5. In addition, it represented the largest change in favor of the entire sample during all periods recovering by 0.5477 points. The U.S. has its best result in 2013 with 0.4550, when its upward trend from previous years is broken and turns downward until 2018, when it picks up slightly.

Mexico had its best performance in 2015 (1.00); it was efficient with its lowest score expressed in 2011 (0.2621) and 2009 (0.2644). The trend remains high from the beginning of the research until 2015, when it fell from 1 to 0.5738 in 2016. This represents Mexico's strongest OTE fall with 0.4262 less points. It rebounds in 2017 obtaining a score of 0.7539, which represents the most important recovery of 0.1801 points.

Overall Technical Efficiency Based on the DEA-CRS Bootstrap Model

The bootstrap technique was systematically applied to each level of efficiency to give the sample statistical validity and reduce the standard error. This was achieved through a random re-sampling with substitution, favoring the robustness of the analysis and bringing the results closer to the values of the universe (Lo *et al.,* 2001).

The highest average is obtained by Russia (0.8904) followed by Iran (0.8442), Nigeria (0.8429), Kuwait (0.8279), and Angola (0.8153) in the first five positions. Saudi Arabia (0.7840) drops 5 places, the largest change. Russia gains one place, Iran gains four, Nigeria one, Kuwait loses one, Angola remains in the same position. Only Mexico and Venezuela alternate their positions, and the rest remain the same as before applying the bootstrap.

Canada obtains the lowest average with 0.2620. Mexico is the second most efficient American country in this exercise with an average of 0.4121, only behind Brazil with 0.5421. Once again, OPEC member countries obtain high PTE scores, now surpassed only by Russia. Venezuela repeats its performance as the lowest in the organization.

2018 is now shown as the year with the best average for the upstream sector of the oil industry (0.7699), like 2015 in the previous exercise. The worst performance was shown in 2009 (0.5250), one year after the model before bootstrap. However, 2008 is the second worst year (0.5290) with a slight difference of 4 thousandths, so the 2008-2009 period showed the lowest average in both situations.

Table 17. *OTE CRS of the Upstream Sector in the Oil Industry with Bootstrap, 2008-2017*

DMU	*Periodo*										*Promedio DMU*
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	
RUSSIA	0.8431	0.8708	0.9285	0.8675	0.8832	0.9130	0.9165	0.9198	0.8411	0.9205	0.8904
IRAN	0.9531	0.8703	0.7962	0.8558	0.8604	0.8323	0.8187	0.8573	0.6958	0.9022	0.8442
NIGERIA	0.5738	0.8153	0.9254	0.9459	0.8106	0.9268	0.8429	0.8967	0.8334	0.8586	0.8429
KUWAIT	0.8188	0.8644	0.8679	0.8207	0.8102	0.8108	0.8489	0.6364	0.8850	0.9155	0.8279
ANGOLA	0.8395	0.8373	0.8790	0.7968	0.7022	0.7532	0.8208	0.7875	0.8812	0.8560	0.8153
SAUDI ARABIA	0.7277	0.7296	0.7685	0.7877	0.7915	0.8199	0.7861	0.7867	0.7727	0.8695	0.7840
NORWAY	0.6417	0.5179	0.6025	0.8424	0.7178	0.8573	0.8878	0.8588	0.7768	0.4719	0.7175
UAE	0.6860	0.5164	0.8793	0.8995	0.9093	0.8723	0.9325	0.6050	0.2847	0.2563	0.6841
BRAZIL	0.2276	0.1782	0.1935	0.3121	0.3302	0.8088	0.8785	0.8150	0.9131	0.7650	0.5422
UK	0.2449	0.2552	0.3645	0.5305	0.4881	0.5901	0.4182	0.7464	0.7915	0.8420	0.5271
MEXICO	0.2360	0.2301	0.2674	0.2289	0.2415	0.3136	0.3869	0.8655	0.5166	0.8347	0.4121
VENEZUELA	0.7283	0.7254	0.7525	0.3261	0.2023	0.2231	0.3161	0.1740	0.1389	0.2901	0.3877
CHINA	0.2552	0.2108	0.3671	0.2775	0.3280	0.2799	0.3777	0.2613	0.1482	0.8678	0.3374
USA	0.0820	0.1408	0.1645	0.3778	0.2601	0.4302	0.3143	0.2683	0.3034	0.9533	0.3295
CANADA	0.0777	0.1131	0.1220	0.1367	0.1725	0.2171	0.2482	0.2880	0.3003	0.9449	0.2620
AVERAGE AN.	0.5290	0.5250	0.5919	0.6004	0.5672	0.6432	0.6529	0.6511	0.6055	0.7699	

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Pure Technical Efficiency Based on the DEA-VRS Model

In the preliminary PTE results, it can be seen how the upstream sector of the oil industry is consistently efficient in countries such as Saudi Arabia, Russia, Iran, Kuwait, and Nigeria, which consistently present a PTE level of 1. The North American countries had their lowest efficiency levels during the initial years. However, USA becomes efficient from the year 2011 until the end of the period; Canada only manages to be efficient in 2017; Mexico presents its highest efficiency values in 2011, 2012, 2013 and 2015, then it drops to 60% in 2016 and rises again to 82% in 2017 showing a PTE recovery.

Seven of the countries under study belong to OPEC, they are: Saudi Arabia, Iran, United Arab Emirates, Kuwait, Venezuela, Nigeria, and Angola. All of them consistently show high levels of efficiency, except Venezuela which has fallen since 2011.

Only Saudi Arabia, Russia, and Angola achieved maximum efficiency over the whole period, while China and Canada maintained the lowest levels through all periods.

The year in which more countries achieved a TE of 1 was 2013. Twelve countries were technically efficient then: USA, Mexico, Saudi Arabia, Russia, Iran, United Arab Emirates, Kuwait, Brazil, Nigeria, Angola, Norway, and United Kingdom. The years in which less countries were efficient were 2008 and 2009, with only 7 countries remaining efficient.

Table 18. *PTE VRS of the Upstream Sector in the Oil Industry, 2008-2017*

DMU	*Periodo*										*Promedio DMU*
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	
SAUDI ARABIA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
RUSSIA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
ANGOLA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
IRAN	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9417	1.0000	0.9087	0.9404	0.9791
NIGERIA	0.6968	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9697
KUWAIT	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.6854	1.0000	1.0000	0.9685
USA	0.6362	0.7685	0.7271	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9132
NORWAY	1.0000	0.5573	1.0000	1.0000	1.0000	1.0000	1.0000	0.9495	1.0000	0.4994	0.9006
UK	0.3458	0.4465	0.3983	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.8191
UAE	0.7934	0.8177	1.0000	1.0000	1.0000	1.0000	1.0000	0.6199	0.4300	0.2696	0.7931
MEXICO	0.2863	0.2703	0.3067	1.0000	1.0000	1.0000	0.9472	1.0000	0.5981	0.8730	0.7282
BRAZIL	0.2382	0.2312	0.2128	0.3486	0.3736	1.0000	0.9862	1.0000	1.0000	0.8004	0.6191
VENEZUELA	1.0000	1.0000	1.0000	0.3423	0.2431	0.3630	0.4926	0.3892	0.4996	0.2967	0.5626
CHINA	0.4089	0.4058	0.3926	0.3669	0.3822	0.3852	0.3916	0.4190	0.4218	0.8833	0.4457
CANADA	0.3008	0.3152	0.3209	0.3154	0.3215	0.3511	0.3710	0.3650	0.3626	1.0000	0.4023
AVERAGE AN.	0.7138	0.7208	0.7572	0.8249	0.8214	0.8733	0.8753	0.8285	0.8147	0.8375	

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

The DMU's with the highest average are Saudi Arabia, Russia, and Angola, achieving a PTE of 1. Mexico obtained 0.7282, which places it in second place for PTE among American countries; however, it remains in 11^{th} place overall, only above Brazil with 0.6191.

Venezuela with 0.5626, China with 0.4457, and Canada with 0.4023 obtained the lowest scores; these results show that American countries except the USA have the lowest PTE scores. On the other hand, 5 of the 7 OPEC countries are among the 6 countries with the highest global scores, they are Saudi Arabia (1), Angola (1), Iran (0.9791), Nigeria (0.9697), and Kuwait (0.9685).

Mexico's performance was below each period's mean before 2010 (1.00); its PTE exceeded the mean from 2011 (1.00) to 2015, the period of maximum efficiency. From that year onwards the score was again below the mean. During 2016 both OTE and PTE suffer the biggest setback, but they recover in the following year. PEMEX EP obtained an average of 0.7228. This places it as the second best DMU in the Americas above Brazil, as opposed to its OTE levels.

The PTE rating with VRS obtained by USA differs quite a lot from its OTE. When considering DMU differentiation by size, the performance of this country turns out to be the best among American countries with an average of 0.9132 and an efficient performance from 2011 to 2018.

The best PTE average is observed during 2013 and 2014 with 0.8733 and 0.8753 respectively. The lowest performance is in 2008 with 0.7138; since then, the overall PTE trend is upwards and only declines slightly during 2016 to recover in 2017.

Canada and the US show the largest improvements in PTE between 2016 and 2017. Canada is the first country going from 0.3626 to 1, which represents an increase of 0.6374 points. While the U.S. improves its score from 0.4217 to 0.8833, an increase of 0.4616 points. Only Venezuela and the United Arab Emirates showed an upward trend in their performance during the first few years, but they changed their trend in 2011 when they began to decline.

The industry's general trend is positive as most countries improved or maintained their PTE levels after each period. However, there is a slight setback in 2015 that eventually comes back to previous levels in 2017.

Pure Technical Efficiency Based on the DEA-VRS Bootstrap Model

The bootstrapping exercise improves the statistical quality of the sample and gives results that are closer to the universe of the study. In this section, the following observations are made about the PTE of the *upstream* sector in the oil industry.

Russia again gains one position compared to the results before *bootstrap* and obtains an average of 0.8975, followed by Iran (0.8885), Angola (0.8414), and Kuwait (0.8376) who gain positions while Saudi Arabia loses four positions again.

The positions at the bottom of table 19 show no change compared to table 18, and the range of averages can be considered significantly close. The trend distribution for each period's average is also similar; it pushes the average down a little but retains the same characteristics: trending upwards until 2014, falling from 2015 to 2016, and slightly recovering in 2017.

Table 19. *PTE VRS Bootstrap of the Upstream Sector in the Oil Industry, 2008-2017*

DMU	*Periodo*										*Promedio DMU*
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	
RUSSIA	0.8469	0.8655	0.8664	0.9061	0.9149	0.9491	0.9416	0.9240	0.8398	0.9205	0.8975
IRAN	0.8501	0.8623	0.8213	0.9048	0.9079	0.9533	0.9146	0.9031	0.8658	0.9022	0.8886
ANGOLA	0.7788	0.8386	0.8011	0.8477	0.8448	0.8831	0.8834	0.8496	0.8315	0.8560	0.8415
KUWAIT	0.7715	0.8617	0.8056	0.8314	0.8373	0.8825	0.9161	0.6621	0.8922	0.9155	0.8376
SAUDI ARABIA	0.7782	0.7232	0.7988	0.8400	0.8444	0.8731	0.8852	0.8529	0.8441	0.8695	0.8310
NIGERIA	0.6265	0.8131	0.8060	0.8460	0.8410	0.8756	0.8887	0.8497	0.8386	0.8586	0.8244
USA	0.6218	0.1405	0.7129	0.9654	0.9425	0.9094	0.8958	0.9641	0.9399	0.9533	0.8046
NORWAY	0.7684	0.5157	0.7984	0.8369	0.9091	0.9000	0.8796	0.9213	0.8448	0.4719	0.7846
UAE	0.7381	0.5174	0.8993	0.8909	0.9120	0.9785	0.9418	0.6036	0.4128	0.2563	0.7151
UK	0.3265	0.2558	0.3749	0.8451	0.8378	0.8772	0.8818	0.8545	0.8388	0.8420	0.6934
MEXICO	0.2570	0.2271	0.2813	0.8496	0.8481	0.8758	0.9096	0.8872	0.5604	0.3847	0.6531
BRAZIL	0.2201	0.1768	0.2024	0.3366	0.3615	0.9429	0.9609	0.8452	0.8981	0.7650	0.5710
VENEZUELA	0.7809	0.7233	0.8039	0.3330	0.2378	0.3570	0.4813	0.3774	0.4820	0.2901	0.4867
CHINA	0.3672	0.2102	0.3674	0.3599	0.3729	0.3807	0.3834	0.4022	0.4070	0.8678	0.4119
CANADA	0.2889	0.1127	0.3154	0.3103	0.3154	0.3461	0.3643	0.3487	0.3442	0.9449	0.3691
AVERAGE AN.	0.6014	0.5229	0.6437	0.7285	0.7285	0.7990	0.8085	0.7497	0.7227	0.7699	

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

The overall industry average after analyzing all observations after bootstrap is 0.7073. Only Norway, USA, Nigeria, Saudi Arabia, Kuwait, Angola, Iran, and Russia are above this score. This is largely due to the consistency of their results compared to the below average countries that show an improvement in their PTE in the last two years.

The models proposed by Banker (1986) and Lo (2001) were used to calculate OTE with CRS and PTE with VRS for all fifteen countries in the sample. The results show a considerable improvement in the 2015 to 2017 period in general and for each case, including non-OPEC countries. Canada also shows a considerable comeback, and Norway falls dramatically in the last year analyzed.

Scale Efficiency of the *Upstream* sector in the oil industry

Scale Efficiency is relevant when the production technology presents variable returns to scale. This type of efficiency shows whether the production unit analyzed has reached the optimal point of scale (Banker, 1984). Through SE, it is possible to identify whether a DMU is efficient in scale. This means that it obtains the expected results given a certain number of inputs, depending on its size compared with the rest of the DMU's.

The most efficient DMU in its scale is Saudi Arabia; both its OTE and PTE reach 1 consistently throughout the period covered in this paper. The USA has the worst score, obtaining the lowest number of outputs with respect to the number of inputs (0.2933), even though the upstream sector of this country employs a large amount of EW, PW and LF compared to other countries. The production of reserves and crude oil is far below the rest of the DMU's with which it was compared.

In this area, for the first time an American country appears at the top of the results: Brazil with (0.9550) is the fifth best in SE, OPEC countries remaining in the top positions: Kuwait (0.9973), Nigeria (0.9847), Angola (0.9351), United Arab Emirates (0.9166), and Iran (0.0906). Russia also maintains a good performance and is placed in the third position.

Mexico is placed in 12th position with an average SE of 0.7103; it is the third best result for American countries. PEMEX EP shows a significant drop between 2011 and 2014. This is just one year after its worst levels of efficiency in its scale; it obtained the highest level of efficiency in 2015, and it reduced a little during 2016 and 2017.

Brazil, unlike Mexico, shows a constant performance with high SE levels. Venezuela, on the other hand, starts 2008 as an efficient DMU in scale until 2011; after 2012, it starts a downward trend to reach its worst result in 2016 with 0.3119.

The overall performance of the *upstream* sector across all periods analyzed is relatively flat, and the averages obtained vary little from each other. The year with the best performance was 2010 with 0.8751, and the worst year was 2012 with an overall result of 0.7886. The mean of all SE observations is 0.8229, very close to 1. This reflects that the industry has been efficient in the scale it operates.

Table 20. *SE of the Upstream Sector in the World Oil Industry, 2008-2017*

DMU	*Periodo*										*Promedio DMU*
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	
SAUDI ARABIA	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
KUWAIT	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9727	1.0000	1.0000	0.9973
RUSSIA	0.9357	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9936
NIGERIA	0.9458	0.9009	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9847
BRAZIL	0.9989	0.8706	0.9558	0.9841	0.9600	0.8776	0.9242	1.0000	1.0000	0.9789	0.9550
ANGOLA	1.0000	1.0000	1.0000	0.8706	0.7798	0.8293	0.8713	1.0000	1.0000	1.0000	0.9351
UAE	0.9349	0.7166	0.9297	1.0000	1.0000	0.9183	1.0000	0.9996	0.7128	0.9541	0.9166
IRAN	1.0000	1.0000	1.0000	1.0000	1.0000	0.8903	0.9265	0.9174	0.8166	0.5148	0.9066
NORWAY	0.6801	0.9974	0.6396	1.0000	0.7520	1.0000	1.0000	0.9228	1.0000	0.8314	0.8823
VENEZUELA	1.0000	1.0000	1.0000	0.9987	0.8814	0.6579	0.6895	0.4888	0.3119	0.5348	0.7563
CHINA	0.7043	0.5758	1.0000	0.8051	0.9260	0.7547	0.9953	0.6625	0.3723	0.3221	0.7118
MEXICO	0.9624	0.9782	0.9854	0.2621	0.2838	0.3526	0.4550	1.0000	0.9594	0.8637	0.7103
UK	0.7760	0.6366	0.9661	0.5654	0.5045	0.6477	0.4617	0.8141	0.8156	0.7457	0.6933
CANADA	0.2803	0.3901	0.4030	0.4592	0.5724	0.6552	0.7064	0.8661	0.8731	0.8644	0.6070
USA	0.1371	0.2099	0.2471	0.4021	0.1692	0.4551	0.3483	0.2851	0.3278	0.3512	0.2933
AVERAGE AN.	0.8237	0.8184	0.8751	0.8232	0.7886	0.8026	0.8252	0.8619	0.8126	0.7974	0.8229

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Scale Efficiency Based on the DEA-VRS Bootstrap Model

The results shown in table 21 are obtained after applying bootstrap to the sample and performing SE assessment. They show a similar order to those units that operate at their optimal scale; it can be observed that OPEC countries continue at the top of the table with values that are closer to 1.

Nigeria stands out with a score of 0.8890 and is placed as the DMU that is closest to the optimal level of scale. It is three positions higher than in the DEA exercise before bootstrap, while the rest of the countries remain in similar positions.

Table 21. *SE Bootstrap of the Upstream Sector in the Oil Industry, 2008-2017*

DMU	*Periodo*										*Promedio DMU*
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	
NIGERIA	0.7978	0.8734	1.0000	0.9737	0.8395	0.9219	0.8261	0.9192	0.8656	0.8726	0.8890
RUSSIA	0.8671	0.8763	0.9334	0.8339	0.8407	0.8379	0.8478	0.8670	0.8723	0.8414	0.8618
KUWAIT	0.9243	0.8737	0.9384	0.8598	0.8428	0.8002	0.8070	0.8371	0.8640	0.8543	0.8602
ANGOLA	0.9389	0.8696	0.9556	0.8187	0.7240	0.7428	0.8093	0.8074	0.9230	0.8768	0.8466
BRAZIL	0.9005	0.8777	0.8325	0.8075	0.7954	0.7472	0.7963	0.8398	0.8855	0.8358	0.8318
UAE	0.8095	0.8694	0.8516	0.8793	0.8684	0.7765	0.8624	0.8729	0.6008	0.7771	0.8168
SAUDI ARABIA	0.8144	0.8787	0.8379	0.8167	0.8164	0.8179	0.7735	0.8034	0.7973	0.8030	0.8159
NORWAY	0.7274	0.8748	0.6572	0.8767	0.6876	0.8297	0.8791	0.8119	0.8009	0.6778	0.7823
IRAN	0.9765	0.8790	0.8443	0.8238	0.8254	0.7604	0.7796	0.8268	0.7000	0.4057	0.7821
UK	0.6533	0.8692	0.8469	0.5467	0.5074	0.5858	0.4131	0.7608	0.8219	0.7177	0.6723
CHINA	0.6053	0.8732	0.8703	0.6716	0.7660	0.6404	0.8580	0.5659	0.3173	0.2565	0.6424
VENEZUELA	0.8123	0.8735	0.8153	0.8530	0.7411	0.5444	0.5721	0.4017	0.2511	0.4339	0.6298
MEXICO	0.7999	0.8824	0.8282	0.2346	0.2480	0.3118	0.3705	0.8497	0.8029	0.7485	0.6077
CANADA	0.2342	0.8739	0.3368	0.3838	0.4764	0.5463	0.5933	0.7193	0.7599	0.7335	0.5657
USA	0.1149	0.8727	0.2010	0.3408	0.2403	0.4121	0.3056	0.2424	0.2812	0.2923	0.3303
AVERAGE AN.	0.7318	0.8745	0.7833	0.7147	0.6813	0.6850	0.6996	0.7417	0.7029	0.6751	

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Mexico, USA, and Canada operate with scale deficiency as they rank in the last three positions of the table. The latter two countries even obtain scores below 0.6, consistently showing their lowest values in each period. The only American country that does not present such behavior is Brazil, which is closer to operating at an optimal level of scale with an average score of 0.8318. However, it had its worst exercise in 2013.

Saudi Arabia is a clear example of constancy; the range between each period and the average obtained is the smallest of all countries. This shows that its operation is consistent and tends to reach the optimal scale; however, it also shows how static its operation is.

The year with the lowest SE level in the upstream sector is 2017 with 0.6751. The downward trend is observed from 2015, coincidentally a year after the lack of agreement on production volumes and prices proposed by OPEC.

VRS Slack Analysis of the Upstream Sector in the Oil Industry

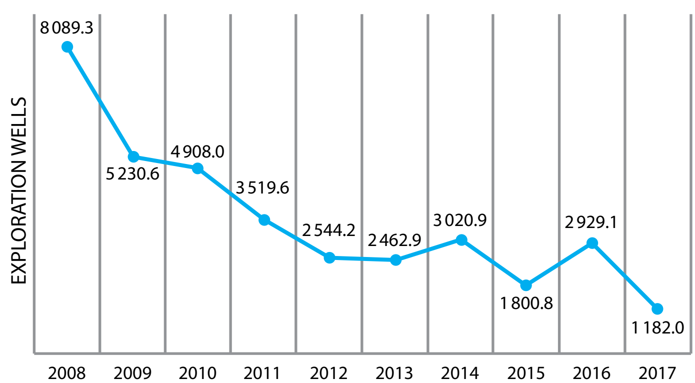
A slack analysis of variables in DEA models sets the guidelines for DMU's to improve their efficiency levels. Thus, the output slack value represents the additional level of output necessary to convert an inefficient DMU into an efficient one. Therefore, an input slack value represents the input reductions necessary to convert a DMU into an efficient one (Lo *et al.*, 2001).

The model selected for this research is output-oriented, the analysis is carried out for each period. Lo (2001) agrees to this; however, it is understood that the inputs are being underutilized and could produce a greater quantity.

For the year 2008, the countries that presented a production of petroleum reserves below the optimal level were: the USA, Canada, Mexico, Brazil, which theoretically could have produced 3098, 3746, 2635, 2517 million barrels equivalent to additional proven oil reserves respectively. This would represent 11995 million additional barrels to global production. This is only if petroleum production does not present a significant shortfall that would affect PTE ratings.

There were considerable slacks in inputs during 2018. USA and Canada underused both EW and PW as follows: 4930 EW and 1655 PW for USA, and 2762 EW and 234 PW for Canada. In terms of labor, the USA does not make efficient use of 114 thousand employees, China 166 thousand employees, Canada 29 thousand employees, and Brazil 11 thousand employees.

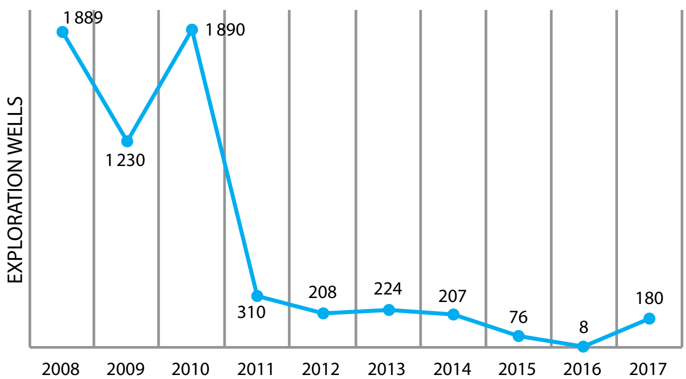
Graph 9. *Slack Exploration Wells in the Upstream Sector, 2008-2017*



Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

During 2009, the production of additional proven oil reserves that could have been incorporated by the countries in the sample are distributed as follows: Canada with 2 993, Mexico with 1 908, Norway with 752, and United Kingdom with 1 029 (million barrels); it is a total of 6 684 million barrels of new proved petroleum reserves.

Graph 10. *Slack Production Wells in the Upstream Sector, 2008-2017*



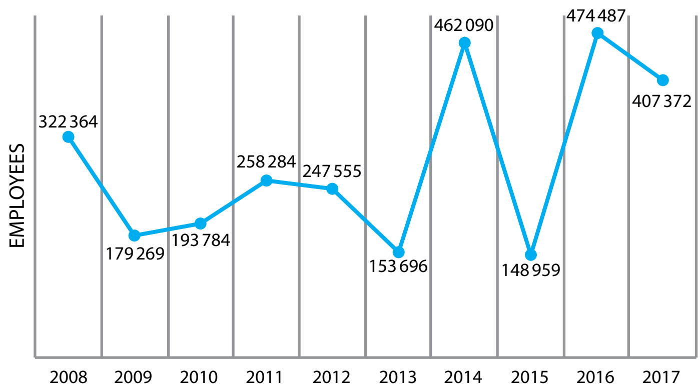
Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Inputs that were not used efficiently during 2009 were: 2 646 exploration wells from the USA, 1 028 from Canada, and 1 278 from China. 1 113 production wells from the USA, 115 from Canada. 31 752 employees from the USA and 147 137 from China.

In 2010, the production of petroleum reserves was far from optimal levels as follows: 8 496 Mb USA, 8 261 Mb Canada, 1 367 Mb Mexico, 9 957 Mb China, 5 113 Mb Brazil, and 1 627 UK. The inputs that should have been better employed were as follows; USA 2 654 EW, 1 656 PW, and 33 321 employees; Canada 1 227 EW and 308 PW; China 864 EW and 160 463 employees.

The only country that could have generated more petroleum reserves in 2011 was Canada, which was 3 016 million barrels short of the optimum level. If significant slacks in total crude oil production were exposed in 2011, Brazil and Venezuela would have reached 472 and 629 million additional barrels respectively. There is a considerable reduction of those inputs that did not reach their highest potential: Canada 1 603 EW, 308 PW and 34 074 employees; China 1 047 EW and 224 209 employees; Venezuela 868 EW.

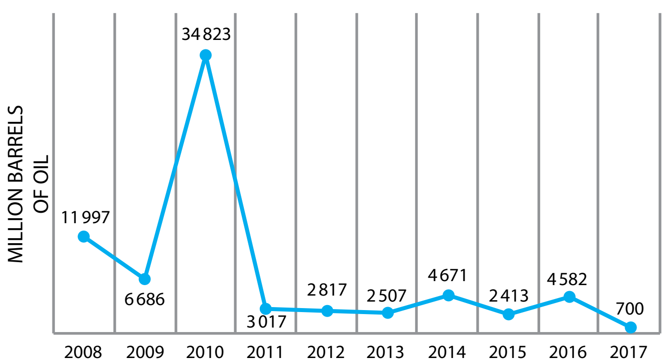
Graph 11. *Slack Labor Force in the Upstream Sector, 2008-2017*



Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

During 2012, Canada would have achieved an additional production of 1 878 Mb in reserves and China of 938 Mb. These countries underused 1 152 and 671 EW respectively. The following year, both countries increased their distances from the frontier. Canada, with 1 878 Mb in reserves, underused 1 015 EW, 224 PW, and 13 352 employees. China, with 634 Mb in PR, underused 1 425 EW and 233 890 employees. Venezuela left its production at 1 161 Mb with the mix of inputs that implemented in 2013.

Graph 12. *Slack Petroleum Reserves in the Upstream Sector, 2008-2017*



Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

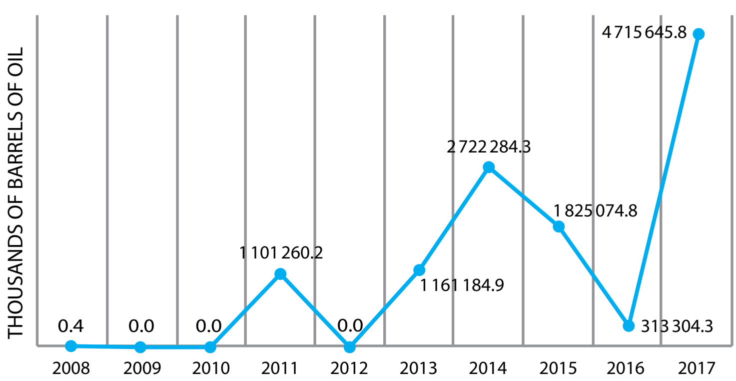
In 2014, Venezuela's total crude oil production fell short of optimal levels by 1 164 Mb with respect to PR, Canada fell short by 3 339 Mb, Mexico by 587 Mb, Iran by 720, Mb and China by 23 Mb. Regarding inputs, Canada 837 EW and 176 PW, Iran 235 EW and 90 381 employees, China 1 513 EW and 233 890 employees, Venezuela 433 EW and 84 106 employees, and Brazil 31 958 employees.

The sum of slacks for each period shows the industry trend for each country. When the trend is downward in the graph, the gap with the production frontier is getting shorter; in other words, countries are getting closer to efficiency. In this case, it represents an improvement in their use and procurement of EW, PW (capital factors), and PR.

On the other hand, the graphs showing an upward trend reveal an increasing gap with the efficiency frontier. The results show that LF and TP have an upward trend, which represents a worsening in their use and procurement (graph 13).

The most significant deficits in 2015 were Venezuela, with a gap in crude oil production of 1 542 Mb; Canada with 1 452 Mb in reserves; for the first time, the United Arab Emirates, Kuwait, and Norway present slacks in the oil reserves that they could have achieved with the technological combination they presented: 315 Mb, 609 Mb, and 354 Mb respectively. During this period, the number of underused inputs was considerably reduced: only 121 EW for the UAE, 355 EW and 50 PW for Venezuela, and 148 944 employees for China.

Graph 13. *Slack Total Production of the Upstream Sector, 2008-2017*



Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Venezuela's crude oil production continued to move away from the efficient frontier now by 313 Mb; this was due to the underutilization of 586 EW and 107 112 employees in 2016. Deficits in petroleum reserves during this stage increased almost twice; Canada with 2 392 Mb, Mexico with 1 116 Mb[1], and Iran with 1 116 Mb. Regarding capital factors, the countries that moved away from effective use were Canada with 434 EW, Iran with 157 EW, China with 1 547 EW, and Venezuela with 586 EW. At that time, there was no slack for PW. About labor force, Canada underused 1 327 employees, Mexico 20 175[2], Iran 90 190, China 250 645, the United Arab Emirates 5 035, and Venezuela 107 113.

The last year analyzed shows an increase in the slack of products compared to the previous year. Mexico, the United Arab Emirates, and Norway show again a deficit in reserves with 52 Mb, 356 thousand barrels, and 170 Mb respectively. The production of crude oil for China and Venezuela was 2 831 Mb and 1 884 Mb less than their possible efficient level. While the underuse of EW and employees decreased, the opposite happened with PW. In 2017, China had 906 EW underused, UAE 202 EW, and Brazil 72 EW. Iran and Venezuela underused 162 PW altogether. Mexico underused 18 323 employees, Iran 78 905, China 221 485, Brazil 43 049 and Venezuela 45 609.

Benchmarking of DMU's in the Upstream Sector of the Oil Industry

Benchmarking analysis makes it possible to identify those countries considered as a reference for those that failed to be efficient having similar characteristics (Delfín & Navarro, 2014). As per table 18, Saudi Arabia was a referential country the greatest number of times (10). In 2009 were Iran, Angola, and Venezuela; in 2010 Iran 10 times; and from 2011, Saudi Arabia prevailed as the most referenced country for PTE with VRS.

[1] The decline in recovered reserves from Cantarell Field started in 2014; however, PEMEX EP achieved viable findings that were added in 2015, but no new ones were reached in 2016 and 2017 (PEMEX, 2019).

[2] It was stated in the Planning document that year that PEMEX would have to adjust, which resulted in chronic layoffs reported until 2019 *(idem)*.

Through all analyzed periods, Saudi Arabia was used by other countries 69 times as an output-oriented PTE reference with VRS. This country was most of the time an adequate model to measure DMU vectors of market imperfections, size, and technology.

Table 22. *Benchmarking VRS of the Upstream Sector in the Oil Industry, 2008-2017*

Clave	*DMU*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
P01	USA	P04(1.00)	P06(1.00) P11(1.00)	P06(1.00)	P01(1.00)	P01(1.00) P06(1.00)	P01(1.00)	P01(1.00)	P01(1.00)	P01(1.00) P05(1.00)	P01(1.00)
P02	CANADA	P04(1.00)	P05(1.00) P06(1.00)	P05(1.00) P06(1.00)	P04(1.00)	P04(1.00)	P04(1.00)	P04(1.00)	P01(1.00) P04(1.00)	P04(1.00) P10(1.00)	P01(1.00) P02(1.00) P04(1.00)
P03	MEXICO	P04(1.00) P06(1.00) P09(1.00)	P04(1.00) P05(1.00) P09(1.00)	P04(1.00) P06(1.00) P13(1.00) P14(1.00)	P03(1.00) P04(1.00) P14(1.00)	P03(1.00) P04(1.00)	P03(1.00) P04(1.00) P15(1.00)	P04(1.00) P15(1.00)	P04(1.00) P10(1.00) P13(1.00)	P04(1.00) P13(1.00) P15(1.00)	P04(1.00) P15(1.00)
P04	SAUDI ARABIA	P04(1.00) P11(1.00)	P04(1.00) P11(1.00) P13(1.00)	P06(1.00) P11(1.00) P14(1.00)	P04(1.00) P08(1.00) P09(1.00)	P04(1.00)	P04(1.00) P14(1.00)	P04(1.00)	P05(1.00) P13(1.00)	P08(1.00) P12(1.00)	P04(1.00)
P05	RUSSIA	P04(1.00) P05(1.00) P09(1.00) P11(1.00)	P05(1.00) P09(1.00) P11(1.00)	P06(1.00) P11(1.00)	P04(1.00)	P04(1.00) P05(1.00)	P05(1.00)	P04(1.00) P09(1.00) P12(1.00)	P04(1.00) P13(1.00)	P05(1.00)	P04(1.00) P05(1.00)
P06	IRAN	P04(1.00) P06(1.00) P11(1.00)	P06(1.00) P11(1.00)	P06(1.00)	P06(1.00)	P06(1.00)	P06(1.00)	P04(1.00) P08(1.00)	P06(1.00)	P04(1.00)	P04(1.00)
P07	CHINA	P09(1.00) P11(1.00) P13(1.00)	P06(1.00) P11(1.00) P13(1.00)	P06(1.00)	P04(1.00) P06(1.00)	P06(1.00)	P06(1.00)	P04(1.00) P08(1.00)	P06(1.00)	P04(1.00) P05(1.00) P14(1.00)	P04(1.00)
P08	UAE	P06(1.00) P09(1.00) P11(1.00) P13(1.00)	P04(1.00) P06(1.00) P11(1.00) P13(1.00)	P06(1.00) P11(1.00)	P08(1.00)	P08(1.00)	P08(1.00)	P08(1.00)	P03(1.00) P04(1.00) P10(1.00)	P04(1.00) P10(1.00) P14(1.00)	P04(1.00) P05(1.00) P09(1.00)
P09	KUWAIT	P09(1.00)	P09(1.00)	P09(1.00)	P09(1.00)	P09(1.00)	P09(1.00)	P09(1.00)	P04(1.00) P06(1.00) P10(1.00)	P09(1.00)	P09(1.00)
P10	BRAZIL	P04(1.00) P06(1.00) P09(1.00)	P04(1.00) P06(1.00) P11(1.00) P13(1.00)	P04(1.00) P06(1.00) P13(1.00)	P04(1.00) P06(1.00) P09(1.00) P13(1.00)	P04(1.00) P06(1.00) P08(1.00) P13(1.00)	P04(1.00) P06(1.00) P14(1.00)	P04(1.00) P08(1.00) P14(1.00)	P04(1.00) P06(1.00) P13(1.00)	P04(1.00) P14(1.00)	P04(1.00) P13(1.00) P15(1.00)
P11	VENEZUELA	P11(1.00)	P11(1.00)	P11(1.00)	P04(1.00) P06(1.00) P09(1.00)	P04(1.00) P06(1.00)	P01(1.00) P04(1.00) P06(1.00)	P04(1.00)	P04(1.00) P06(1.00)	P05(1.00) P14(1.00)	P04(1.00)
P12	NIGERIA	P04(1.00) P05(1.00) P09(1.00) P11(1.00)	P09(1.00) P13(1.00)	P11(1.00) P12(1.00) P13(1.00) P14(1.00)	P12(1.00)	P12(1.00)	P04(1.00) P05(1.00) P09(1.00)	P12(1.00)	P12(1.00)	P12(1.00)	P12(1.00)
P13	ANGOLA	P09(1.00) P11(1.00) P13(1.00)	P13(1.00)	P13(1.00)	P13(1.00)	P13(1.00)	P13(1.00)	P13(1.00)	P13(1.00)	P04(1.00) P12(1.00) P13(1.00) P14(1.00)	P13(1.00)
P14	NORWAY	P04(1.00) P09(1.00) P14(1.00)	P04(1.00) P06(1.00) P13(1.00)	P14(1.00)	P14(1.00)	P14(1.00)	P14(1.00)	P14(1.00)	P03(1.00) P12(1.00) P15(1.00)	P14(1.00)	P04(1.00) P13(1.00)
P15	UK	P04(1.00) P06(1.00)	P04(1.00) P06(1.00) P13(1.00)	P04(1.00) P06(1.00) P13(1.00)	P15(1.00)	P15(1.00)	P15(1.00)	P15(1.00)	P15(1.00)	P15(1.00)	P15(1.00)

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

The consequent order of mostly mentioned countries were Iran (41), Angola (30), Kuwait (25), and Venezuela (21). The latter accumulates all its references only in the first three years analyzed, while the rest were more evenly referred to during the time covered by the analysis (table 23).

After Venezuela, the USA is the American country most often used as a benchmark; it was selected on 10 occasions, but 8 of which are with itself. Mexico is placed in 12th position with only 5 times as an agent of comparison for its efficient performance.

Five out of seven DMU's corresponding to OPEC countries included in this work occupied the top positions. They not only served as a reference to themselves but were also constantly referred to by all countries in the total sample. Other countries, like Russia, stood out in the results as efficient in mainly all aspects, but their conditions did not make them the most required referents.

Table 23. *Frequent DMU's as Benchmarking Referents for VRS Upstream Sector of the Oil Industry, 2008-2017*

DMU	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*TOTAL*
SAUDI ARABIA	10	6	3	6	6	5	8	7	8	10	69
IRAN	5	8	10	4	5	4	0	5	0	0	41
ANGOLA	1	8	5	2	2	1	1	5	2	3	30
KUWAIT	9	4	1	4	1	2	1	0	1	2	25
VENEZUELA	8	8	5	0	0	0	0	0	0	0	21
NORWAY	1	0	4	2	1	1	2	0	6	0	17
RUSSIA	2	3	1	0	1	2	0	0	4	2	15
UK	0	0	0	1	1	1	2	2	2	3	12
USA	0	0	0	1	1	2	1	2	1	2	10
NIGERIA	0	0	1	1	1	0	2	1	3	1	10
UAE	0	0	0	1	1	1	4	0	0	0	7
MEXICO	0	0	0	1	1	1	0	2	0	0	5
BRAZIL	0	0	0	0	0	0	0	3	1	0	4
CANADA	0	0	0	0	0	0	0	0	0	1	1
CHINA	0	0	0	0	0	0	0	0	0	0	0

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

OTE Component Analysis in the Upstream Sector

Separating OTE components is useful to identify whether the use of resources in their physical form resulted in the best possible scenario, or the DMU size and the yields of production factors generated the efficiency levels observed in the sample. Even though this does not generate a causal relationship with PTE, the SE towards OTE will show which one had a greater impact.

Prior to a dynamic productivity analysis, decomposing TE helps identify periods with important changes in the results; then it is possible to compare the DMU's historical and compositional information within the industry.

Table 24 shows that most OPEC countries have the best efficiency levels, including Russia ranking 2nd best. The American countries take most of the lower positions in the table, showing the worst performances in many efficiency components; only China is the third worst performer.

Table 24. *Technical Efficiency and Its Components (Average) 2008-2017*

DMU	*ETP*	*EEs*	*ETG*
SAUDI ARABIA	1.0000	1.0000	1.0000
RUSSIA	1.0000	0.9936	0.9936
KUWAIT	0.9685	0.9973	0.9667
NIGERIA	0.9697	0.9847	0.9560
ANGOLA	1.0000	0.9351	0.9351
IRAN	0.9791	0.9066	0.8906
NORWAY	0.9006	0.8823	0.7919
UAE	0.7931	0.9166	0.7359
BRAZIL	0.6191	0.9550	0.5917
UK	0.8191	0.6933	0.5492
VENEZUELA	0.5626	0.7563	0.4639
MEXICO	0.7282	0.7103	0.4500
CHINA	0.4457	0.7118	0.2963
USA	0.9132	0.2933	0.2767
CANADA	0.4023	0.6070	0.2655

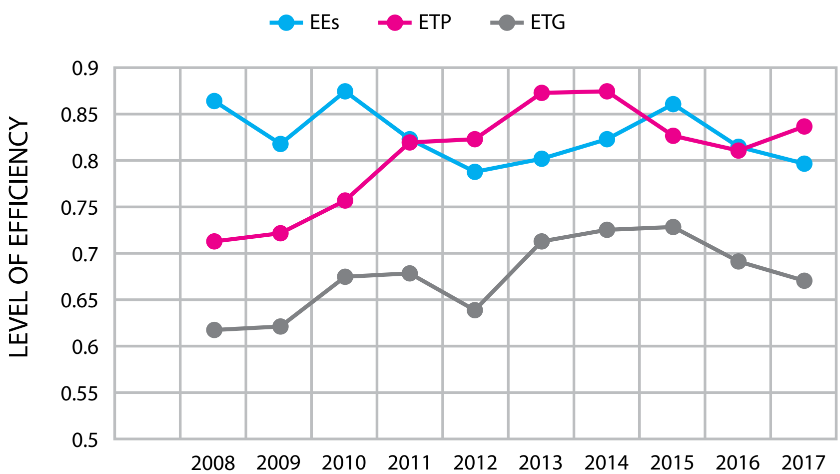
Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

The USA, even with a unitary use of inputs, provided products on par with the most efficient countries; however, its yields per production unit were well below the level of other DMU's (including Canada, which had the worst result). So, the USA's SE considerably decreased its OTE, obtaining the second worst score with 0.2767.

Even though Mexico is not one of the most efficient countries, its results show consistency between its PTE and SE. However, its physical elements are not efficiently used, and the yields obtained for each one are lower. The combined effect of these ratings places PEMEX EP in 12th place globally and the third best performer in the Americas[3].

The period with the best efficiency levels was 2014-2015, while 2008 and 2009 showed the lowest average efficiencies (graph 11). The efficiency value with the greatest SE variation is 0.29 and only one DMU as efficient in scale. As for PTE, the lowest level was 0.40 with three countries operating efficiently in a purely technical fashion.

Graph 11. *Evolution of Technical Efficiency Components, 2008-2017*



Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

[3] In 2018 a process of renegotiating NAFTA began, meanwhile it remained the most efficient country.

Total Factor Productivity and Its Components through the Malmquist Index

The Malmquist index explains the efficiency changes of a unit from one period to another. This is a consequence of movements in the frontier and in the units analyzed (Giménez, 2004). This index also analyzes changes in the frontiers resulting from a DEA analysis; this change is called technological change. Finally, this technique makes it possible to measure the impact of efficiency and technological changes on the productivity of all production factors.

The Malmquist index evaluates a DMU's productivity change between two periods and is an example of a "comparative statics" analysis. It is defined as the result of catch-up and frontier-shift. Catch-up is the degree to which a DMU improves or worsens its efficiency, while frontier-shift reflects the change in efficient frontiers between two periods of time (Cooper *et al.*, 2008).

Table 26 exposes both effects on the change of all OTE components. We can observe that more than 70% of the countries perceive a catch-up effect greater than 1 for both PTE and SE, and consequently on OTE. In contrast, the frontier shift effect for TC is only greater than 1 in 46% of the countries.

Catch Up Effect of the Upstream Sector in the Oil Industry

PTE changes in the main producing countries correspond to the catch-up effect. Those countries with values > 1 show efficiency improvements; this means that they maximized their outputs from one period to another with a combination of inputs less than or equal to that of the previous year, compared to the DMU's of their level.

Results in table 25 show that 80% of the countries improved PTE in their operations, and the American countries obtained the best results: The USA improved efficiency by an average of 40.51%, Canada by 33.65%, Mexico by 25.65%, and Brazil by 23.40%. The only exception in this continent is Venezuela, which dropped its PTE by an average of 3.57% and is the country with the second worst result in the sample.

The USA had the highest catch-up value in 2010 with an improvement greater than 400%. This progress concurs with the highest value obtained by Canada during the same period, in which it reached about 180% PTE improvement. This effect seems to be repeated the following year in Mexico, which also obtains its highest score with an improvement of 200%. This same year, Brent and West Texas' crude oil spot prices reached their highest levels since 2008 (Standard & Poor's, 2018).

The countries with values < 1 are those in which their PTE worsened; this means that their outputs stayed far from the levels of previous periods, even though the same or lesser amount of inputs were used. Twenty percent of the selected countries show this behavior. However, the values are not far below 1, which suggests that their operation has kept the same PTE rating, and they have remained stable throughout the period under study.

In general, there are no significantly low catch-up values in the results; even the lowest values achieved were accompanied by a significant improvement in the following period. This was due to investment or simply because it is easier to recover from bad results. Such is the case of the U.S., which in 2009 obtained the lowest score of all observations with a 77.41% drop. However, it obtained the greatest advance of the entire sample the following year.

Table 25. *Catch Up Effect of the Upstream Sector in the Oil Industry, 2009-2017*

	EFECTO CATCH UP ETP									
	2008-2009	*2009-2010*	*2010-2011*	*2011-2012*	*2012-2013*	*2013-2014*	*2014-2015*	*2015-2016*	*2016-2017*	*PROM. DMU*
USA	0.2259	5.0745	1.3541	0.9764	0.9648	0.9851	1.0761	0.9750	1.0143	1.4051
CANADA	0.3901	2.7984	0.9839	1.0165	1.0973	1.0527	0.9572	0.9870	2.7450	1.3365
MEXICO	0.8839	1.2384	3.0206	0.9983	1.0327	1.0386	0.9753	0.6317	1.4894	1.2565
BRAZIL	0.8033	1.1447	1.6631	1.0740	2.6080	1.0191	0.8796	1.0626	0.8517	1.2340
CHINA	0.6725	1.7475	0.9795	1.0363	1.0209	1.0070	1.0490	1.0119	2.1324	1.1730
UK	0.7835	1.4658	2.2543	0.9914	1.0470	1.0052	0.9691	0.9816	1.0039	1.1669
NIGERIA	1.2978	0.9913	1.0497	0.9940	1.0412	1.0149	0.9561	0.9870	1.0238	1.0395
KUWAIT	1.1169	0.9349	1.0321	1.0071	1.0540	1.0381	0.7227	1.3475	1.0261	1.0310
SAUDI ARABIA	0.9293	1.1045	1.0516	1.0053	1.0340	1.0139	0.9635	0.9897	1.0301	1.0135
ANGOLA	1.0768	0.9553	1.0581	0.9966	1.0454	1.0003	0.9617	0.9788	1.0294	1.0114
RUSSIA	1.0220	1.0011	1.0458	1.0097	1.0373	0.9922	0.9813	0.9089	1.0962	1.0105
IRAN	1.0143	0.9525	1.1016	1.0035	1.0500	0.9594	0.9874	0.9587	1.0420	1.0077
NORWAY	0.6711	1.5483	1.0483	1.0863	0.9899	0.9774	1.0474	0.9170	0.5586	0.9827
VENEZUELA	0.9263	1.1113	0.4142	0.7140	1.5015	1.3482	0.7841	1.2772	0.6020	0.9643
UAE	0.7010	1.7381	0.9907	1.0237	1.0729	0.9625	0.6409	0.6838	0.6209	0.9372
AVERAGE X PERIOD	0.8276	1.5871	1.2698	0.9955	1.1731	1.0276	0.9301	0.9799	1.1511	1.1047

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

It is important to maintain an average catch up effect above 1, but it must come together with improvements in each period. It is more difficult to increase the score consistently than to recover after a significant drop in values.

Frontier Shift Effect of the Upstream Sector in the Oil Industry

The DMU operation is modified over time, which causes changes in their efficiency. This happens when there is a change in the combination of inputs and outputs obtained, also considering the DMU's that were taken as a reference for their efficient behavior. This shift is called frontier shift; when it is > 1, a DMU performance shows technological progress. When the value is < 1, the DMU shows technological regression.

Table 26. *Frontier Shift Effect of the Upstream Sector in the Oil Industry, 2009-2017*

	EFECTO FRONTIER SHIFT CT									
	2008-2009	*2009-2010*	*2010-2011*	*2011-2012*	*2012-2013*	*2013-2014*	*2014-2015*	*2015-2016*	*2016-2017*	*PROM DMU*
BRAZIL	1.1904	0.9304	0.6516	0.8482	1.1090	0.6044	2.4439	0.9348	1.2836	1.1107
IRAN	1.3166	1.3885	0.3402	0.8053	0.9833	0.9566	1.1244	1.1555	1.4745	1.0606
NORWAY	1.1639	0.9082	0.8011	0.6465	1.2310	0.7112	1.0736	1.7775	1.2045	1.0575
USA	0.7562	0.9854	0.4339	2.2461	0.3758	1.7077	1.1255	1.0315	0.8199	1.0535
VENEZUELA	0.6503	1.8867	0.1883	0.8532	0.9288	0.9494	1.6321	1.4675	0.7035	1.0289
ANGOLA	0.9988	0.6809	0.7688	1.0251	0.9149	0.9500	1.4597	1.1798	1.1359	1.0127
UK	1.0867	0.6080	0.7200	0.7720	1.1571	0.7668	1.1742	0.9061	1.8528	1.0049
NIGERIA	0.6809	0.8912	0.9008	1.5228	0.5691	1.2966	0.9835	1.3561	0.7459	0.9941
UAE	1.1372	0.5426	0.7253	0.7875	1.0142	0.8988	1.1343	1.5017	1.1698	0.9902
MEXICO	0.9161	1.0223	0.9526	0.8573	0.9276	1.0537	1.1589	0.8866	1.1184	0.9882
CHINA	1.0637	0.6915	0.4808	0.8220	1.1064	0.8335	1.5451	1.4453	0.8838	0.9858
SAUDI ARABIA	1.0488	1.0547	0.9431	0.9151	0.8136	1.0771	0.8743	1.0746	0.9570	0.9731
CANADA	0.7664	0.8282	0.8852	1.0341	0.8992	0.9868	1.0129	1.1438	1.0364	0.9548
KUWAIT	0.6834	0.8935	0.9712	1.1107	0.9488	0.7846	1.0019	1.2000	0.8962	0.9434
RUSSIA	0.9167	0.8653	0.9733	1.0005	0.8601	0.9620	0.9936	1.0210	0.7299	0.9247
AVERAGE X PERIOD	0.9584	0.9452	0.7157	1.0164	0.9226	0.9693	1.2492	1.2055	1.0675	1.0055

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

As shown in table 26, 2014 and 2015 were the years with the greatest technological progress; the score obtained by Brazil stands out with an advance of 144%, which is the highest of all values obtained in the results. Only the U.S. presents a progress higher than 100% in 2012.

Forty-seven percent of the countries in the sample obtained technological progress with a maximum of 11% obtained by Brazil (table 26). The rest of the countries are relatively close to 1. Those countries with technological regression are also close to 1; this implies that TC occurs mainly when the combination of inputs is not reaching the desired results, and investment is required to improve efficiency and increase inputs, which happens less frequently.

Total Factor Productivity in the Upstream Sector of the Oil Industry

TFP refers to changes in productivity derived from changes in PTE and TC. More specifically, it refers to how the combination of inputs used, and outputs obtained, explain productivity changes from one period to another.

As per table 27, USA presented SE problems during the efficiency analysis; it shows an improvement in all variables, being PTE the most relevant with an improvement of 40.51%. However, there is also a relatively discrete technological progress of 5.35%. On the other hand, USA obtained the highest catch-up effect values in PTE and SE. The latter had a 25% improvement, which means that its operation consistently improved both variables.

Brazil had the second highest TFP; its greatest improvement was PTE with a catch-up effect of 2.61 in 2013. Its most relevant technological change happened in 2017 with a 28% improvement in its frontier shift effect. With this global TC result, Brazil is positioned as the DMU with the second-best technological progress (table 27).

Results are also favorable for Mexico, showing one of the best behaviors in all the TFP components. It reached fourth place with an additional 21.22% of productivity in its production factors. Mexico also showed improvements in all types of efficiency, but with a technological regression of 2.1%; this situation does not considerably compromise TFP. In this approach, PEMEX EP obtained its highest technological progress in 2015 with a frontier shift effect 16% higher than 1.

Table 27. *TFP of the Upstream Sector in the Oil Industry, 2009-2017*

	PTF									
	2008-2009	*2009-2010*	*2010-2011*	*2011-2012*	*2012-2013*	*2013-2014*	*2014-2015*	*2015-2016*	*2016-2017*	*PROM DMU*
USA	0.1709	5.0002	0.5875	2.1930	0.3625	1.6822	1.2113	1.0057	0.8316	1.4494
BRAZIL	0.9563	1.0650	1.0837	0.9110	2.8923	0.6160	2.1497	0.9934	1.0933	1.3067
CANADA	0.2990	2.3177	0.8709	1.0512	0.9867	1.0388	0.9695	1.1290	2.8449	1.2786
MEXICO	0.8097	1.2660	2.8775	0.8558	0.9579	1.0944	1.1303	0.5600	1.6658	1.2464
CHINA	0.6090	1.2084	0.4710	0.8518	1.1296	0.8394	1.6208	1.4624	1.8847	1.1197
UK	0.8514	0.8912	1.6232	0.7653	1.2116	0.7708	1.1378	0.8895	1.8600	1.1112
VENEZUELA	0.6024	2.0967	0.0780	0.6093	1.3946	1.2800	1.2796	1.8743	0.4235	1.0709
IRAN	1.3355	1.3225	0.3748	0.8081	1.0325	0.9178	1.1102	1.1078	1.5364	1.0606
ANGOLA	1.0755	0.6505	0.8135	1.0215	0.9564	0.9503	1.4038	1.1548	1.1692	1.0217
NIGERIA	0.8838	0.8834	0.9456	1.5137	0.5925	1.3159	0.9403	1.3384	0.7637	1.0197
NORWAY	0.7810	1.4063	0.8398	0.7022	1.2186	0.6951	1.1244	1.6299	0.6728	1.0078
SAUDI ARABIA	0.9747	1.1649	0.9917	0.9199	0.8412	1.0920	0.8424	1.0635	0.9858	0.9862
KUWAIT	0.7633	0.8353	1.0023	1.1186	1.0000	0.8145	0.7241	1.6169	0.9196	0.9772
RUSSIA	0.9368	0.8662	1.0178	1.0103	0.8922	0.9545	0.9750	0.9279	0.8001	0.9312
UAE	0.7971	0.9430	0.7186	0.8062	1.0881	0.8651	0.7270	1.0269	0.7264	0.8554
AVERAGE X PERIOD	0.7897	1.4612	0.9531	1.0092	1.1038	0.9951	1.1564	1.1854	1.2119	1.0962

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

OPEC countries constantly show themselves as referents in the efficient frontier of the DEA model. However, they do not show considerable changes, so their *catch-up* effects are discrete and in some cases with improvements barely above 1. Most of them, excluding Angola, had technological regression that jeopardized the effect on TFP.

Table 28 shows that the main effect on TFP was the changes in PTE. In tune with the results derived from the DEA model, the *upstream* sector in the world oil industry showed an upward trend in efficiency and better use of resources needed for maximum output. Nevertheless, the labor factor showed an upward trend in underutilization in recent years; this effect is evident in technological change. Capital factors, on the other hand, were effectively employed throughout the periods analyzed.

Table 28. *TFP Components (Average) of the Upstream Sector in the Oil Industry, 2008-2017*

DMU	*EFECTO CATCH UP*			*EFECTO FRONTIER SHIFT*	
	ETG	*EEs*	*ETP*	*CT*	*PTF*
USA	1.3462	1.2500	1.4051	1.0535	1.4494
BRAZIL	1.2172	1.0003	1.2340	1.1107	1.3067
CANADA	1.3587	1.1398	1.3365	0.9548	1.2786
MEXICO	1.1917	1.1070	1.2565	0.9882	1.2464
CHINA	1.0771	0.9707	1.1730	0.9858	1.1197
UK	1.1612	1.0546	1.1669	1.0049	1.1112
VENEZUELA	0.8781	0.9708	0.9643	1.0289	1.0709
IRAN	0.9314	0.9380	1.0077	1.0606	1.0606
ANGOLA	1.0031	1.0031	1.0114	1.0127	1.0217
NIGERIA	1.0530	1.0070	1.0395	0.9941	1.0197
NORWAY	1.0051	1.0657	0.9827	1.0575	1.0078
SAUDI ARABIA	1.0000	1.0000	1.0135	0.9731	0.9862
KUWAIT	1.0185	1.0001	1.0310	0.9434	0.9772
RUSSIA	1.0076	1.0076	1.0105	0.9247	0.9312
UAE	0.9348	1.0220	0.9372	0.9902	0.8554

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

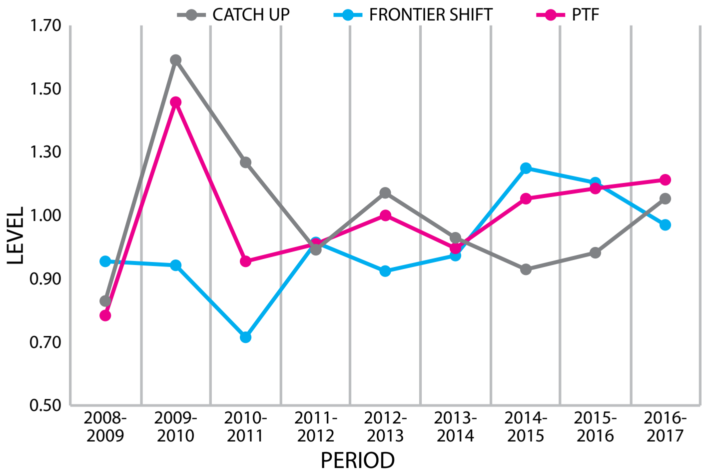
Table 28 reaffirms an improvement over time in the DMU's catch up effect. This produced an industry average of almost 80% in all intervals with increased efficiency of all types. The interval changes from 2012 to 2013 presented the greatest OTE progress.

In contrast, only 44% of all time intervals had a frontier shift greater than 1. There were greatest advances in 2015 after periods of constant technological regression; the 2014-2015 interval had the highest technological progress with 25%.

67% of the analyzed periods presented TFP improvements; the most prominent was 2014-2015 with an advance of 31%. This period was characterized by having the greatest technological progress and a deficit in PTE changes, as well as a small advance in SE and OTE.

Brazil and the United Kingdom reached the highest score in the following year with the greatest TFP increase of 21% in 2017. That year was characterized by a positive result in all components, but the second year came with worse results in the catch-up effect keeping a low technological advance of 6.75%.

Graph 12. *Development of TFP Components, 2008-2017*



Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Venezuela presented the worst setbacks during the intervals ending in 2009, 2011, and 2012: 35%, 36%, and 46% respectively. This happened when its PTE and SE declined, and it had the lowest TC levels. Especially the period ending in 2012 represents a PTE fall of 29%, a SE deficit of 22%, and a 38% lower OTE. The worst OTE drop came in 2011 with a deficit of 66%, which is the most extensive TE setback of all results.

Table 29. *Temporary Evolution of TFP Components, 2008-2017*

PERIOD	*CATCH UP EFFECT*			*FRONTIER SHIFT EFFECT*	
	CHANGES IN ETG	*CHANGES IN EEs*	*CHANGES IN ETP*	*CT*	*PTF*
2008-2009	1.06850	1.04685	0.82764	0.95841	0.78975
2009-2010	1.14663	1.10789	1.58710	0.94516	1.46117
2010-2011	1.13241	0.99743	1.26984	0.71575	0.95305
2011-2012	0.94561	0.95323	0.99553	1.01643	1.00919
2012-2013	1.27002	1.13581	1.17313	0.92259	1.10378
2013-2014	1.05070	1.02980	1.02763	0.96929	0.99512
2014-2015	1.05594	1.09964	0.93009	1.24919	1.15642
2015-2016	0.93713	0.93563	0.97988	1.20545	1.18536
2016-2017	1.10334	1.01566	1.15106	1.06748	1.21186

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2019).

Table 29 reveals that the *upstream* sector of the oil industry experienced catch up and frontier shift effects from 2008 to 2011. During these years, we can observe PTE improvement and technological regression. The meeting point of these two variables occurs in 2012, which suggests that countries improved their efficiency even employing obsolete technology mixes. However, they invested heavily in 2012 before PTE levels continued to decline.

Less changes can be observed from 2012 to 2017 but the same behavior as in the previous cycle. Efficiency levels recovered through technological investment and progression. In both cycles, the upward TFP trend is maintained after 2010.

VI. Conclusions and Recommendations

This section presents the conclusions derived from the analysis of technical efficiency and TFP. The analysis was carried out through the DEA and Malmquist index methodological tools for the upstream sector of the main oil producing countries within the 2008-2017 period. Additional recommendations are included to provide a technically and economically feasible solution to the problems of the industry through the DMU's under study. Finally, some limitations and future lines of research are included.

Conclusions

The economic development of countries is linked to their energy consumption, and the current supply is almost 80% dependent on the oil industry (Ahmed, 2017). Future projections show that national energy consumption will increase by about 64% by 2040 (EIA, 2017). It is estimated that the refined product and petrochemical industries will continue to grow by an average of 7% annually; this is largely due to product diversification and demand increase (WB, 2009).

There is a proved increase in the use of alternative energy sources, which helps promoting sustainable development[1]. However, it is not yet a viable

[1] A type of development that satisfies present needs without compromising the opportunities and capabilities that future generations will need to meet theirs (Estrella & Vázquez, 2017).

measure for large-scale industrial and domestic consumption, and its use has been circumscribed to developed economies. In developing countries, the adoption of alternative energies has been more complex and difficult to implement (Sathaye *et al.,* 2009; Kaygusuz, 2012).

International oil companies (IOC's) and national oil companies (NOC's) had usually had heterogeneous operations but are gradually standardizing their activities over time. This is possible since private investment allows participation in most State-run companies. This is seen in many NOC's that made reforms since 2010 to their oil production and to their energy generation and distribution policies (Ohene-Asare *et al.,* 2017). The results obtained in this research suggest that the NOC's included in the sample have improved their PTE levels and increased their TFP, catching up with the performance of IOC's.

OPEC's main goal is to consolidate its members' petroleum activities and strengthen their infrastructure to respond to market competition and generate conditions for equitable participation (OPEC, 2020). Since its creation, member countries have increased their petroleum production and reserves to become owners of large market shares (WB, 2009). This allows OPEC members to exert pressure on world production and international prices, which has a direct impact on the rest of the countries.

Production and revenues are directly related to petroleum prices. In periods when OPEC fails to negotiate production limits with non-members, prices have dropped significantly. Brent and West Texas blends fell from \$94.34 and \$100.06 USD respectively in 2008 to \$61.39 and \$61.92 USD in 2009. Similar conditions happened in 2014, so Brent and West Texas blends' prices dropped from \$97.07 and \$93.28 USD to \$51.2 and \$48.71 USD respectively. However, this time there was no price recovery (Standard & Poor's, 2018).

Results show that the difference between potential revenues and price made NOC's and IOC's move towards improving their operational efficiency. This had the effect of a global fall in both production and world petroleum reserves. As exposed in this research, efficiency levels improved and the changes in production factors led to a consistent increase in productivity in most countries analyzed. The recovery of non-OPEC countries stands out, especially the USA, Brazil, Canada, and Mexico. In general, the way companies participate in the industry allows them to have similar technological characteristics and focus their efforts and limited resources on improving their technical efficiency.

Except for Venezuela, OPEC member countries performed better than non-member countries. The catch up and frontier shift effects are close to 1, therefore, their TFP shows little growth without any significant changes. Only Saudi Arabia, Kuwait, and the United Arab Emirates had a minimal reduction. These countries altogether present the highest production in the upstream sector; in addition, most of them are geographically close, which facilitates the use of infrastructure already installed for trading. Relatively little investment is applied to new exploration and production wells, which in turn offer good performance per unit. Angola is located in the west coast of Africa and takes advantage of its strategic position in the Atlantic Ocean for trading and procurement with neighboring African countries (Kaygusuz, 2012).

China, Iran, and Venezuela are countries with national oil companies that have shown less openness to private participation. Their main problems are PTE and SE because of not reaching their optimal of crude oil production and proven reserves. They underuse the labor force available to them, sometimes in excess. Nahar (2006) describes how a national oil company's focus on social burden gives preference to labor over returns, which limits its ability to invest in capital assets.

The economies of Saudi Arabia and Russia always showed the highest levels of production efficiency with a moderate mix of inputs, making them the best performing countries. During the benchmarking analysis, these two countries were consistently selected as reference for the efficient frontier; they did not present PTE problems when compared to other DMU's of their size, and they operated at optimal scale. As for the TFP analysis, these economies were in lower levels, presenting technological backwardness and a static catch up effect. These results do not pose a problem but prove that these countries present PTE values with few changes through the periods due to being referents of the efficient frontier. This can be confirmed as their TFP value is close to 1.

The analysis showed that USA had the highest TFP increase. This result is obtained during the succession of the periods analyzed; its efficiency levels fell but quickly recovered and maintained growing trends. The most difficult period was 2008-2009. USA's OTE did not show output maximization with the inputs used. Compared to all DMU's analyzed, this affected its performance by not operating at optimal scale and obtaining low returns out of its inputs. However, when compared with the DMU's of the same size, USA ranked as the most efficient of the American countries, especially for producing the most by using more capital inputs. On the other hand, its TC remained basically at the same distance from the efficient frontier during the whole exercise, close to 1. It had a catch-up effect of 20%, higher than all DMU's including Brazil.

Brazil's economy shows the second highest TFP value; it is the only country with a significant evolution in frontier shift and catch-up effects. PTE changes show an improvement of 23.4%; this was due to a considerable change in that variable in 2013, when a field was found offshore under a layer of salt (Husseini, 2018). This event helped increase production considerably. Additionally, Brazil continued to operate close to optimal scale during the entire period of this research.

On the other hand, Mexico maintained low OTE levels with some improvement since 2015; the structure of its subsidiaries was modified that year, and the energy reform changed the entry policies in petroleum exploitation operations. The upstream sector significantly improved SE since 2015; the observed changes were mainly in the number of employees, not in EW or PW. These two increased steadily until 2017, only achieving a considerable increase in crude barrels but not recovering their PR.

Compared to similar DMU's, Mexico ranked as the second-best country in the Americas. This effect is attributed to PEMEX's structural change when outsourcing upstream operations to subsidiary PEMEX EP, which had a direct impact on the workforce employed. Regarding the energy reform, a weak impact is observed during 2017 as only 31 Mb/d were produced by private companies that had obtained by bidding an exploitation contract; PEMEX produced 1 715 Mb/d. (CNH, 2020).

The upstream sector shows countercyclical behavior between its catch up and frontier shift effects; when PTE levels improved, there were technological setbacks. This first cycle happened from 2008 to 2012, which concurs with the recovery of crude oil prices. So, until revenues increased, investment was renewed to change the technology used in the upstream sector. From 2012 to 2014, after efficiency levels increased, the cycle repeated with a smaller technological setback. In 2015, revenue reduction came again due to low prices, so efficiency improvements were distanced and there was a new technological setback. In 2016, investment in better technology reduced PTE levels. This suggests a direct relationship between PTE levels and crude oil prices in the upstream sector of the main oil producing countries; there is also an adaptation period when using new technology.

The OTE of the main oil-producing countries was positively affected by both the PTE and the SE. However, changes in the latter were greater and therefore had a greater impact on OTE. When most DMU's analyzed were compared with those of the same level, they presented ratings close to 1; the exception were China, Canada, and Venezuela, which presented few years with an above-average evaluation. SE shows a greater segregation among countries operating close to optimum scale; those that did not, obtained a lower ratio of output returns with respect to the inputs used. The most affected country with this condition was the USA. Table A7 at annexes shows a clear example of surplus capital inputs used to obtain production levels like those of Saudi Arabia, a country that uses a lower amount of EW and PW.

After 2012, SE and PTE levels remained more stable until 2017. PTE recovered after 2016 while SE continued downward since 2015; this also affects OTE as it keeps the same trend as SE. Thus, the industry is experiencing problems of scale; planning input combinations does not bring the same yields as in the past, and this results in lower production. In addition, the discovery and partial exploitation of deposits is not carried out at full because of a lack of the necessary technology.

TFP dynamics were clearly impacted by changes in efficiency, while TC was more stable. In this area, North American countries stand out as their efficiency improvements are the most representative all results obtained. Mexico had an average of 24.64%, Canada 27.86%, Brazil 30.67%, and USA 44.94%. There is a clear catch-up effect in these countries; their PTE values fluctuated between the periods in which crude oil prices were reduced, showing lower income, and the times of recovery when production increased.

The impact of TC is minor; there is no example of any country whose TFP has been deeply affected by this variable. This reveals the countries' consistency remaining efficient throughout the period; therefore, their TFP and TC showed values close to 1.

Thus, it can be observed that TC and changes in PTE positively explain TFP; however, the catch-up effect had a greater impact on TFP values. We can infer that crude oil prices have an impact on PTE, and they also have a direct effect on the TFP of the upstream sector in the main oil producing countries.

Agreements between OPEC and non-OPEC countries are crucial in determining production targets, infrastructure planning, market supply, and international crude oil prices. Measuring TE and TFP of the upstream sector in the oil industry helps to decide whether to minimize the use of available resources and maximize all possible benefits.

The production process would require monitoring efficiency and TFP during the transition to sustainable development and efficient energy consumption. Crude oil should be gradually replaced as it is now the main energy source; then the changes would meet the market's goals and distribution. The upstream sector is also the first link in the productive chain of the oil industry. Apart from fuels, it includes other derivatives destined to such important industries as the petrochemical and pharmaceutical (Sueyoshi & Wang, 2018). The versatility of the oil industry and its critical value for energy supply and national income guarantee its continued existence, as long as its operation is carried out efficiently.

Finally, the upstream sector of the oil industry in the main oil-producing countries is technically efficient and has consistently improved its PTE levels, thus showing growth in TFP. This industry will continue growing if it stays focused on keeping these levels of PTE and solves specific SE problems arising.

Recommendations

The oil industry faces challenges that jeopardize its operations; there is a gradual transition to renewable energies, there are new technologies for extraction, a substitution of oil products by other products less harmful to the environment, and stricter environmental policies (Alpizar-Castro & Rodríguez-Monroy, 2016). Despite this, petroleum remains the main source of energy supply; many of its products do not have a viable substitute, and economic growth generates greater demand for energy (Rozo *et al.*, 2019).

Petroleum production has reduced because of an improved efficiency in energy supply (Díaz, 2018). However, this change seems to respond more to the fall in crude oil prices than to a supposed reduction in demand. During times of reduced revenues, producers with more costly operations or with more debt are mostly affected and are impelled to reduce their production and limit their investment projects. In addition, they completely absorb the risk of continuing their operations (Hartley & Medlock III, 2011). Additionally, current proven oil reserves reveal a sufficient supply for another 80 years (WB, 2018).

In this context, we suggest keeping the industry active and invest in maintaining and monitoring TE as well as TFP changes. This will help locate the necessary elements in time to meet the goals and actively adapt to market changes.

The upstream sector absorbs a large part of the investments and is the first stage in the production process in the entire industry. High costs or low productivity would mean higher costs for the rest of the stages. This is crucial for the oil industry because countries like Mexico take a stock price as a reference and run the risk of operating at costs that exceed revenues, which causes a market restriction for them.

Price volatility makes the upstream sector of the oil industry a high-risk business. In addition, the companies involved use their own capital and/or are in debt, so the risk is even higher. Thus, risk consolidation is a useful measure, so the total production of an oil company is not compromised. For this reason, NOC's and IOC's should seek financing tools with appropriate monitoring measures to diversify risk and protect their operation. Privatization reforms such as Mexico's in the electricity sector show how supply efficiency can be improved and projects that would not have been possible without private intervention can be settled (Navarro, 2005). The current indebtedness policy makes companies such as PEMEX lower their guarantees to the minimum level due to the possibility of failing to pay the credit obtained in 2019 (Reuters, 2020).

As the upstream sector cycles through PTE and TC changes, these variables start to drift apart again. Only those DMU's that adapt their processes to improve efficiency and invest in the best available technology will continue to benefit from the increase in energy demand; they may even increase their production if a competitor must decline.

We analyzed the TE and TFP of the resources employed by the upstream sector in physical units. This allowed us to identify similarities between NOC's and IOC's, and it proved that state ownership is obsolete. All NOC's allow access to private initiative for exploration and production. This technological aspect of the industry is essential to improve and maintain optimal efficiency levels and provide stability in input procurement for best returns and TFP increase.

OPEC has succeeded in meeting its goal of balancing the market conditions of the oil industry; it has even managed to be in control of important variables such as price. There should be new goals with a vision of a sustainable future, The industry must align its goals to new trends and participate in their implementation. This way, it will continue generating income from energy supply.

Technology should also be implemented to make fossil fuels less polluting. Otherwise, only those derivatives that generate less waste and allow alternative sources for domestic use should be used. The upstream sector has the responsibility to evaluate deposits efficiently. Crude oil should be obtained in the least polluting way possible during the development and production stages; for this, it should always keep the most optimal quality such as the super-light[2]. This requires prioritizing investment in shallow and deep waters over onshore fields and avoiding practices such as fracking.

OPEC countries that are geographically close take advantage of this condition and generate production and supply agreements to favor their production costs, energy sovereignity, and market share (OPEC, 2019). Canada, USA, and Mexico share infrastructure and trade agreements that facilitate their international operations. However, such operations have been affected as Mexico does not carry out decisive and reciprocal investment

[2] The world industry of liquid hydrocarbons classifies petroleum according to its API density (international parameter of the American Petroleum Institute), which classifies crude oil qualities. Super-light crude oil is the least dense and allows faster treatment (Viñas *et al.*, 2009).

protection and international arbitration to differentiate between State and investors (ISDS). If otherwise, there would be a greater certainty of investment in oil projects, which often involve investment terms of up to 40 years (AMEXHI, 2017).

Petroleum projects should be planned for the long term and should have continuity in times of political transition; they should be led mainly by experts in the field and not by governments that rule for shorter periods. As mentioned earlier, the pure form of a NOC is obsolete, and operations allowing private participation involve investment protection, transparency of operations, and profit sharing, as is the case of IOC's. Governments must change their role as owners and directors of a company to facilitators who keep the conditions to make the company attractive for investment; they should also ensure to achieve the goals set to deliver profits. Investors and experts must provide certainty on the business conditions, so the decisions of the company would not be unilateral, even if the State exerts greater force.

This measure would attract continuous investment and raise the possibility of consolidating projects and accelerating production for those already active; the expected profits would still be revenue for the government. On the contrary, production is limited to using existing assets when there is debt to cover; no new projects can be undertaken, and revenues are earmarked to pay liabilities and interest.

If Mexico consolidates its existing projects, it will considerably increase production just like Brazil; there would be an efficiency improvement and the possibility of using the best available technology to constantly increase the productivity of production factors. New investors can be attracted by new revenues to independently undertake projects that would otherwise be impossible, thus increasing State participation in the oil industry including the upstream sector.

Limitations and future lines of research

There are more methodological and theoretical tools that can explain efficiency, TC and TFP. These concepts can even be explained quantitatively and qualitatively through other variables and different approaches. This research focuses on non-parametric models: the DEA and the Malmquist index. It aims at illustrating the levels reached by each variable and demonstrating in physical units which inputs and outputs are responsible for the performance achieved.

We analyzed the *upstream* sector of the oil industry including countries that achieved the highest production in the 2008-2017 period; it was a sufficiently representative sample of the industry's overall behavior. This research can be considered a first-stage work of efficiency and TFP within this line of research.

Additionally, we suggest future studies of the downstream and midstream sectors in the oil industry, particularly using tools such as DEA Network. We also propose an analysis of participation in energy supply with alternative energy sources as well as the evolution of efficiency and productivity over time. This will help identify substitution patterns, efficient levels, and productivity improvements.

The negative effects of the industry must be considered as well. The DEA offers alternatives to include bad outputs[3] and compare their results when they are managed and left to their natural disposition. Sueyoshi (2018) used this type of tool to relate productivity to sustainability. A perspective of gradual substitution by alternative energy can be added to determine the extent to which this is feasible.

Parametric methods offer an alternative to strengthen the research. The results would have better statistical quality through econometric models like DEA stochastic; robustness tests also allow predictions with low error margins and causality analysis. All methodological tools complement each other and offer new perspectives to analyze a problem from various angles and/or discover new problems to study. Research is also strengthened by using joint knowledge and techniques; collaborating with other researchers and experts from different institutions and countries helps to broaden our vision of the problems to be studied, observe how differently they affect other communities, and identify potential solutions with greater social impact.

[3] Bad output or undesirable output is an undesirable product obtained in the production process, which moves the DMU away from the efficient frontier (Cherchye *et al.*, 2015).

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Annexes

Table A1. *Inputs and Outputs of the Upstream Sector in the Oil Industry, 2008-2009.*

			2008		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	4 957	1 782	167 100	412 144 670	2 476 144 670
Canada	2 789	361	81 765	0	1 170 555 000
Mexico	65	111	50 273	221 925 231	10 18 925 231
Saudi Arab.	27	127	52 312	3 745 898 020	3 891 898 020
Russia	260	335	32 101	3 577 914 593	3 638 777 593
Iran	294	52	125 788	3 038 777 593	3 638 777 593
China	637	52	284 821	2 354 748 615	1 387 748 615
UAE	124	14	21 300	938 853 000	938 853 000
Kuwait	92	11	5 751	976 743 650	976 743 650
Brazil	147	59	74 140	0	661 416 865
Venezuela	1 350	108	78 739	74 025 500 640	1 079 500 640
Nigeria	105	20	6 600	736 338 590	736 338 590
Angola	99	6	6 501	692 165 195	692 165 195
Norway	56	25	23 600	92 265 605	769 265 605
UK	168	22	21 400	490 648 630	493 648 630
			2009		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	2 866	1 172	155 300	5 127 007 410	2 651 007 410
Canada	1 248	313	75 530	0	1 168 730 000
Mexico	75	122	50 544	540 040 641	949 540 641
Saudi Arab.	27	102	53 111	4 054 119 634	3 527 119 634
Russia	270	320	32 101	2 905 171 665	3 707 384 665
Iran	160	52	126 946	3 097 384 665	3 707 384 665

China	1 458	52	265 499	1 816 015 130	1 385 015 130
UAE	173	11	22 000	818 197 870	818 197 870
Kuwait	118	25	6 130	825 487 650	825 487 650
Brazil	170	66	76 919	888 900 015	711 900 015
Venezuela	775	120	91 949	39 900 491 900	1 050 491 900
Nigeria	140	18	6 600	672 324 160	672 324 160
Angola	60	5	7 985	634 692 660	634 692 660
Norway	65	22	25 300	309 854 030	722 854 030
UK	154	14	21 500	0	474 920 845

Inputs: Exploration Wells (EW), Production Wells (PW), Labor Force (LF).
Outputs: Petroleum Reserves (PR) and Total Production (TP).
Source: Authors' own design (2019). Based on WB database (2019), OPEC Statistical Yearbook (2009), API Annual Report (2009), Canadian Petroleum Industry Database (2018), PEMEX Institutional Database (2019), CNPC Annual Report (2009), NIOC Annual Report (2010), ROSEFT Statistical Yearbook (2010), PDVSA and BP Securities and Exchange reports (2009, 2010).

Table A2. *Inputs and Outputs of the Upstream Sector in the Oil Industry, 2010-2011*

			2010		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	2 840	1 711	161 000	6 873 453 620	2 755 453 620
Canada	1 569	398	85 400	1 048 984 251	1 216 180 000
Mexico	39	80	49 802	625 012 089	940 612 089
Saudi Arab.	24	98	54 798	3 603 217 766	3 677 217 766
Russia	415	294	35 977	4 026 069 056	3 789 670 256
Iran	186	54	127 679	17 949 670 256	3 789 670 256
China	1 050	54	288 142	3 137 886 000	1 487 886 000
UAE	182	13	32 000	848 197 585	848 197 585
Kuwait	268	24	6 528	843 923 800	843 923 800
Brazil	185	75	80 492	835 977 180	749 977 180
Venezuela	890	125	99 867	86 369 577 870	1 041 577 870
Nigeria	94	35	7 000	747 618 185	747 618 185
Angola	118	11	7 625	196 524 000	641 524 000
Norway	45	19	26 800	656 497 030	656 497 030
UK	140	20	21 100	138 862 860	438 862 860
			2011		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	3 125	2 003	180 300	7 653 479 885	2 868 479 885
Canada	1 636	429	90 140	611 827 034	1 282 975 000
Mexico	33	105	51 713	735 604 617	931 704 617
Saudi Arab.	33	121	56 066	4 956 467 206	4 067 467 206
Russia	365	300	37 229	3 755 544 019	3 846 446 219
Iran	204	123	133 954	7 256 446 219	3 846 446 219

China	1 109	123	293 143	1 958 020 880	1 479 020 880
UAE	266	19	33 000	935 922 050	935 922 050
Kuwait	523	32	6 807	970 421 850	970 421 850
Brazil	212	86	81 918	1 624 460 050	768 460 050
Venezuela	1 050	116	104 187	2 121 531 055	1 051 531 055
Nigeria	124	38	7 112	0	720 804 920
Angola	112	22	7 895	590 587 155	590 587 155
Norway	52	10	28 700	0	613 245 990
UK	58	16	22 400	367 207 155	367 207 155

Inputs: Exploration Wells (EW), Production Wells (PW), Labor Force (LF).
Outputs: Petroleum Reserves (PR) and Total Production (TP).
Source: Authors' own design (2019). Based on WB database (2019), OPEC Statistical Yearbook (2009), API Annual Report (2009), Canadian Petroleum Industry Database (2018), PEMEX Institutional Database (2019), CNPC Annual Report (2009), NIOC Annual Report (2012), ROSEFT Statistical Yearbook (2012), PDVSA and BP Securities and Exchange reports (2009, 2012).

Table A3. *Inputs and Outputs of the Upstream Sector in the Oil Industry, 2012-2013*

			2012		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	3 040	1 784	191 600	7 654 820 570	3 249 820 570
Canada	1 190	353	74 705	904 327 334	1 365 100 000
Mexico	37	114	51 998	944 287 791	929 987 791
Saudi Arab.	38	148	54 041	4 691 608 428	4 246 608 428
Russia	308	320	39 180	3 673 064 349	3 890 927 949
Iran	323	133	150 878	6 610 927 949	3 890 927 949
China	994	133	292 455	2 168 069 860	1 487 069 860
UAE	304	26	37 000	968 345 000	968 345 000
Kuwait	533	31	7 094	1 086 809 400	1 086 809 400
Brazil	154	71	85 065	1 065 382 530	752 382 530
Venezuela	788	149	132 086	1 187 434 450	1 023 434 450
Nigeria	107	44	6 800	1 605 237 010	713 237 010
Angola	127	27	8 569	621 960 365	621 960 365
Norway	42	25	30 600	605 469 080	559 469 080
UK	40	21	24 200	317 055 425	317 055 425
			2013		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	4 120	1 774	193 200	7 958 994 205	3 675 994 205
Canada	1 065	372	70 635	781 436 348	1 460 000 000
Mexico	38	98	53 404	978 576 393	920 576 393
Saudi Arab.	49	148	57 283	4 097 473 047	4 158 473 047
Russia	410	304	45 280	3 470 088 036	3 945 257 636
Iran	321	138	152 111	4 445 257 636	3 945 257 636

China	1 746	138	292 455	1 467 777 145	1 519 777 145
UAE	277	30	50 000	1 020 734 910	1 020 734 910
Kuwait	590	31	7 351	1 067 497 250	1 067 497 250
Brazil	171	54	86 111	2 634 708 900	738 708 900
Venezuela	415	186	140 626	1 633 162 390	1 018 162 390
Nigeria	114	59	6 700	572 106 705	640 106 705
Angola	115	28	8 892	576 939 095	620 939 095
Norway	59	14	31 800	993 212 905	534 212 905
UK	57	12	24 700	469 567 010	290 567 010

Inputs: Exploration Wells (EW), Production Wells (PW), Labor Force (LF).
Outputs: Petroleum Reserves (PR) and Total Production (TP).
Source: Authors' own design (2019). Based on WB database (2019), OPEC Statistical Yearbook (2009), API Annual Report (2009), Canadian Petroleum Industry Database (2018), PEMEX Institutional Database (2019), CNPC Annual Report (2009), NIOC Annual Report (2014), ROSEFT Statistical Yearbook (2014), PDVSA and BP Securities and Exchange reports (2009, 2014).

Table A4. *Inputs and Outputs of the Upstream Sector in the Oil Industry, 2014-2015*

			2014		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	4 302	1 881	200 300	10 794 390 445	4 295 390 445
Canada	1 016	374	66 125	677 372 865	1 558 915 000
Mexico	24	72	52 403	456 700 147	886 500 147
Saudi Arab.	49	145	61 907	4 988 232 206	4 199 232 206
Russia	395	307	47 470	2 111 544 150	3 964 068 550
Iran	306	135	152 123	3 694 068 550	3 694 068 550
China	1 584	135	295 632	1 809 044 100	1 536 044 100
UAE	292	30	60 000	1 019 810 000	1 019 810 000
Kuwait	596	45	9 043	1 046 374 700	1 046 374 700
Brazil	158	42	80 908	1 316 923 890	822 923 890
Venezuela	669	221	152 072	2 582 161 045	979 161 045
Nigeria	141	46	6 700	1 036 572 155	659 572 155
Angola	87	37	8 473	15 596 120	603 596 120
Norway	57	14	31 900	223 816 125	551 816 125
UK	19	20	24 400	286 257 885	283 257 885
			2015		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	4 950	711	187 200	0	4 653 847 820
Canada	255	209	70 350	958 298 348	1 601 985 000
Mexico	21	19	45 240	406 293 468	827 393 468
Saudi Arab.	52	161	65 282	4 254 923 807	4 377 923 807
Russia	288	322	51 560	3 229 671 727	4 018 363 727
Iran	288	130	153 201	4 888 363 727	4 018 363 727
China	1 588	130	302 145	2 048 463 830	1 565 463 830

UAE	219	51	65 000	1 090 943 025	1 090 943 025
Kuwait	146	38	78 470	1 043 420 025	1 043 420 025
Brazil	131	13	68 829	1 529 613 040	889 613 040
Venezuela	635	182	150 032	1 893 662 915	968 662 915
Nigeria	116	29	6 700	252 089 715	638 089 715
Angola	92	30	8 279	1 745 979 820	644 979 820
Norway	56	17	29 500	214 114 140	572 114 140
UK	13	9	21 700	94 105 100	321 105 100

Inputs: Exploration Wells (EW), Production Wells (PW), Labor Force (LF).
Outputs: Petroleum Reserves (PR) and Total Production (TP).
Source: Authors' own design (2019). Based on WB database (2019), OPEC Statistical Yearbook (2009), API Annual Report (2009), Canadian Petroleum Industry Database (2018), PEMEX Institutional Database (2019), CNPC Annual Report (2009), NIOC Annual Report (2016), ROSEFT Statistical Yearbook (2016), PDVSA and BP Securities and Exchange reports (2009, 2016).

Table A5. *Inputs and Outputs of the Upstream Sector in the Oil Industry, 2016-2017*

			2016		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	5 120	634	152 500	6 492 519 190	4 513 519 190
Canada	484	144	66 620	672 574 444	1 631 550 000
Mexico	26	42	49 319	-	786 037 047
SaudiArab.	49	145	65 266	4 279 643 858	4 526 643 858
Russia	310	311	54 730	7 909 125 355	4 113 325 244
Iran	206	153	155 456	2 913 325 244	4 113 325 244
China	1 656	153	304 121	1 941 970 565	1 453 970 565
UAE	271	79	62 121	1 127 223 660	1 127 223 660
Kuwait	622	58	9 818	1 078 306 725	1 078 306 725
Brazil	131	13	68 829	-	916 133 210
Venezuela	736	138	146 226	2 237 963 595	865 963 595
Nigeria	76	9	6 500	911 950 630	520 950 630
Angola	67	10	7 980	627 391 300	628 391 300
Norway	36	16	28 100	2 061 318 415	589 318 415
UK	17	11	18 700	142 910 030	333 910 030
			2017		
DMU	*EW*	*PW*	*LF*	*PR*	*TP*
USA	5 830	930	144 500	4 765 802 445	4 765 802 445
Canada	380	205	71 125	131 492 351	4 765 802 445
Mexico	24	15	42 455	-	711 116 058
SaudiArab.	111	50	70 762	4 362 057 538	4 362 057 538

Russia	365	332	51 930	4 125 194 011	4 108 901 133
Iran	216	157	151 021	4 108 901 133	4 108 901 133
China	1 713	157	301 213	3 896 559 980	1 395 559 980
UAE	364	59	64 212	1 082 781 990	1 082 781 990
Kuwait	555	78	10 001	987 046 140	987 046 140
Brazil	123	14	62 703	590 955 905	956 955 905
Venezuela	478	189	121 103	1 301 702 730	742 702 730
Nigeria	76	13	6 610	560 508 235	560 508 235
Angola	43	7	7 537	-	595 766 870
Norway	36	16	26 700	344 590 070	579 590 070
UK	12	5	17 700	-	325 289 825

Inputs: Exploration Wells (EW), Production Wells (PW), Labor Force (LF).
Outputs: Petroleum Reserves (PR) and Total Production (TP).
Source: Authors' own design (2019). Based on WB database (2019), OPEC Statistical Yearbook (2009), API Annual Report (2009), Canadian Petroleum Industry Database (2018), PEMEX Institutional Database (2019), CNPC Annual Report (2009), NIOC Annual Report (2016), ROSEFT Statistical Yearbook (2016), PDVSA and BP Securities and Exchange reports (2009, 2016).

Table A6. *Slacks of Inputs and Outputs of the Upstream Sector in the Oil Industry, 2008-2017*

DMU	*Input Exploration Wells Period*									
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
USA	4 930.0	2 646.3	2 654.0							
Canada	2 762.0	1 028.4	1 277.4	1 603.0	1 152.0	1 016.0	837.4		434.4	
Mexico	19.5	23.6								
Saudi Arabia										
Russia										
Iran							235.9		157.0	
China	310.3	1 278.5	864.0	1 047.8	671.0	1 425.0	1 513.9	1 300.0	1 547.2	906.6
UAE	2.1	100.4						121.6	203.8	202.6
Kuwait								2.6		
Brazil		67.5	91.0							72.8
Venezuela		0.0		868.8	721.2	21.9	433.8	355.5	586.7	
Nigeria	8.7									
Angola										
Norway								21.1		
UK	56.7	85.9	21.6							
Total	8 089.3	5 230.6	4 908.0	3 519.6	2 544.2	2 462.9	3 020.9	1 800.8	2 929.1	1 182.0

DMU	*Input Production Wells Period*									
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*

USA	1 654.8	1 113.8	1 656.6							
Canada	234.0	115.7	233.3	308.0	205.0	224.0	176.1	25.2		
Mexico							31.2			4.5
Saudi Arabia										
Russia										
Iran									8.0	90.8
China				1.7						
UAE										
Kuwait										
Brazil										
Venezuela					2.5			50.9		82.5
Nigeria										
Angola										
Norway										1.8
UK										
Total	1 888.8	1 229.5	1 889.9	309.7	207.5	224.0	207.3	76.1	8.0	179.8

DMU	*Input Labor Period*									
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
USA	114 788.0	31 752.3	33 321.0							
Canada	29 453.0			34 074.0	20 664.0	13 352.0		15.0	1 327.0	
Mexico							21 751.8		20 176.0	18 323.2
Saudi Arabia					0.0					
Russia										
Iran							90 381.8		90 190.0	78 905.2
China	166 707.0	147 137.2	160 463.0	224 209.7	141 577.0	140 344.0	233 890.8	148 944.0	250 645.4	221 485.1
UAE									5 035.7	
Kuwait										
Brazil	11 416.5				17 048.3		31 958.9			43 049.8
Venezuela					68 265.9		84 106.3		107 112.9	45 609.1
Nigeria										
Angola										
Norway		379.4								
UK										
Total	322 364.5	179 268.8	193 784.0	258 283.7	247 555.2	153 696.0	462 089.7	148 959.0	474 487.0	407 372.4

Source: Authors' design based on the DEA methodology and calculations made in RStudio (2020).

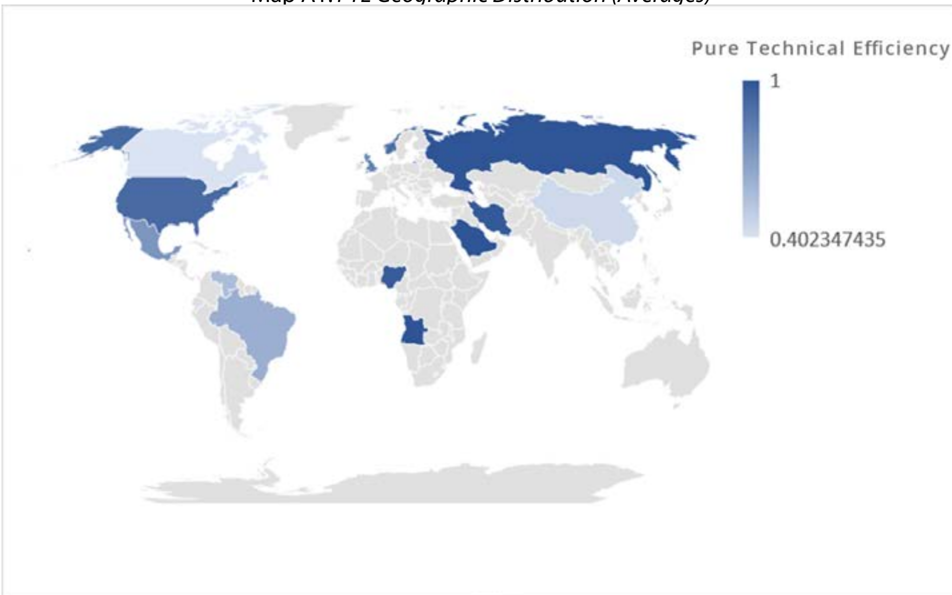
Table A7. *Slacks Outputs of the upstream sector in the oil industry, 2008-2017*

DMU	*Output New Proven Oil Reserves Period*									
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
USA	3 098.1		8 496.4							
Canada	3 745.9	2 993.2	8 261.5	3 016.8	1 878.4	1 871.7	3 339.3	1 452.9	2 392.5	
Mexico	2 634.7	1 908.2	1 366.6	0.1			587.8		1 116.3	528.7
Saudi Arabia	0.4									
Russia		1.0					0.2			
Iran		0.7		0.2			720.4		1 073.6	
China			9 957.4		938.2	635.0	23.2			
UAE								315.9		0.4
Kuwait								609.0		
Brazil	2 516.9		5 113.3							
Venezuela		0.1								
Nigeria										
Angola										
Norway	0.9	752.9						35.5		170.4
UK		1 029.4	1 628.0							
Total	11 997.0	6 685.5	34 823.4	3 017.1	2 816.6	2 506.8	4 670.9	2 413.3	4 582.4	699.5

DMU	*Output Total New Production Period*									
	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
USA										
Canada										
Mexico										
Saudi Arabia										
Russia										
Iran										
China								282 609.9		2 831 288.2
UAE										
Kuwait										
Brazil				472 184.9			506 778.9			
Venezuela				629 075.2		1 161 184.8	2 215 505.3	1 542 464.8	313 304.3	1 884 357.6
Nigeria										
Angola										
Norway	0.4									
UK										
Total	0.4			1 101 260.2		1 161 184.9	2 722 284.3	1 825 074.8	313 304.3	4 715 645.8

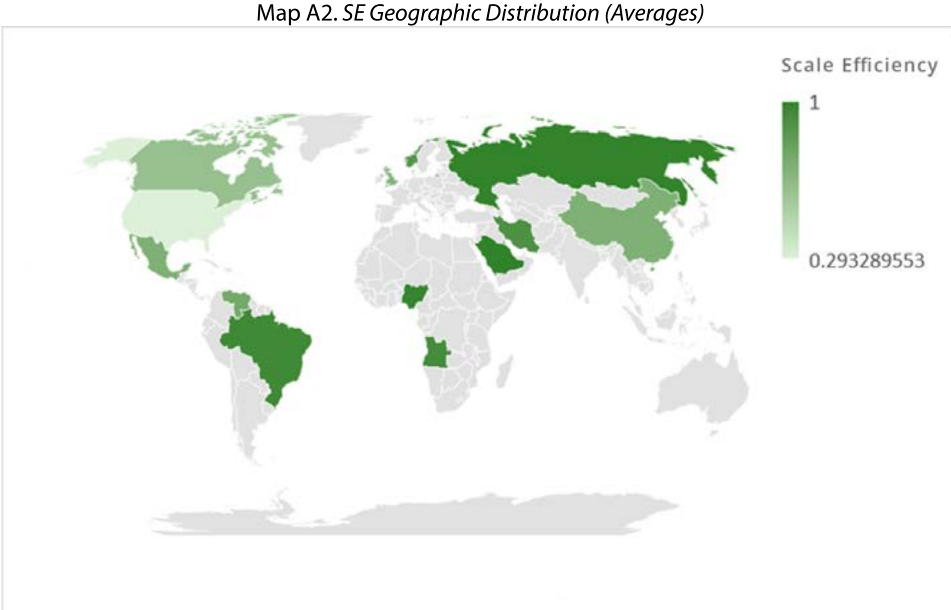
Source: Authors' design based on the DEA methodology and calculations made in RStudio (2020).

Map A1. *PTE Geographic Distribution (Averages)*



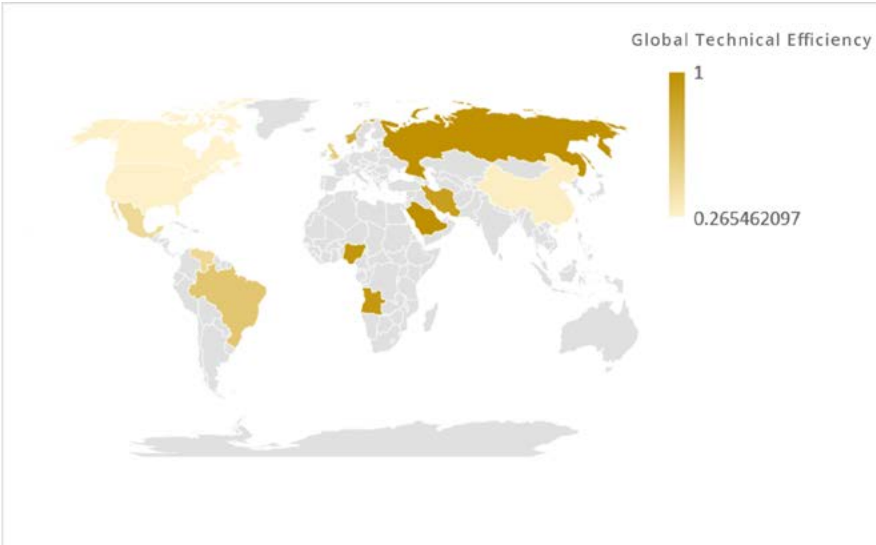
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A2. *SE Geographic Distribution (Averages)*



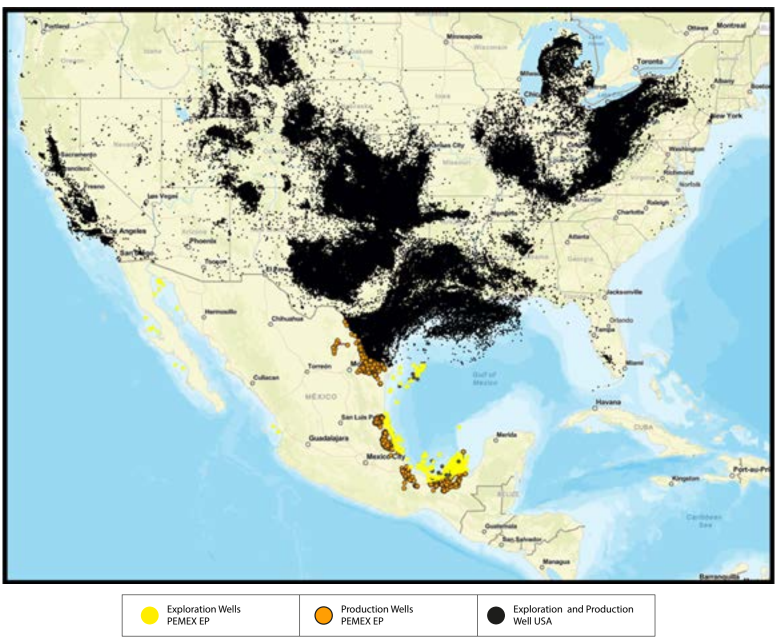
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A3. *GTE Geographic Distribution (Averages)*



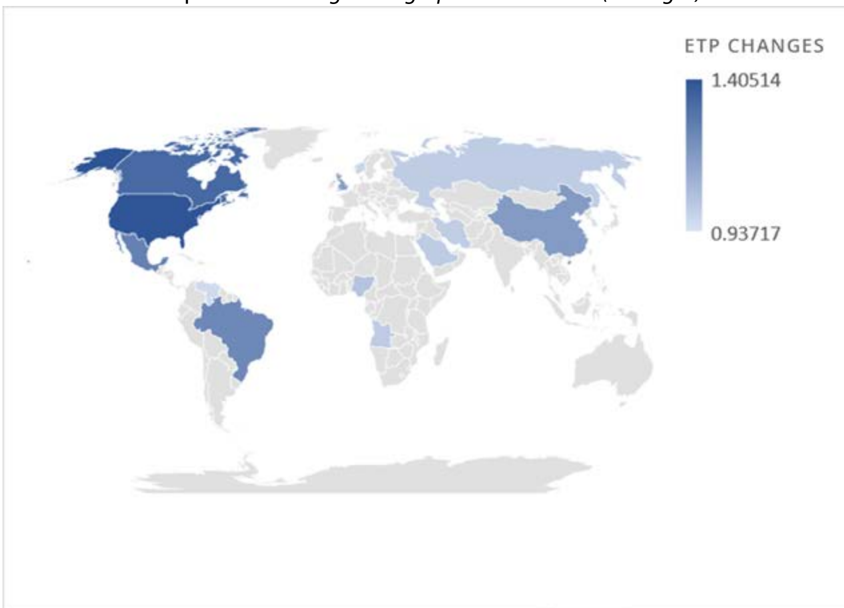
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A4. *Distribution of Exploration and Production Wells Mexico-USA, 2018*



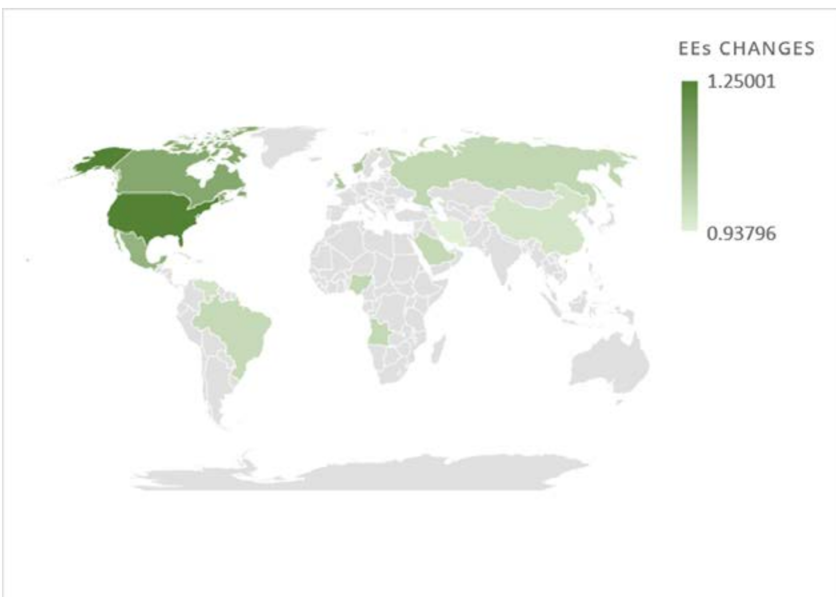
Source: Comisión Nacional de Hidrocarburos (2019), retreived from: https://mapa.hidrocarburos.gob.mx.

Map A5. *PTE Changes Geographic Distribution (Averages)*



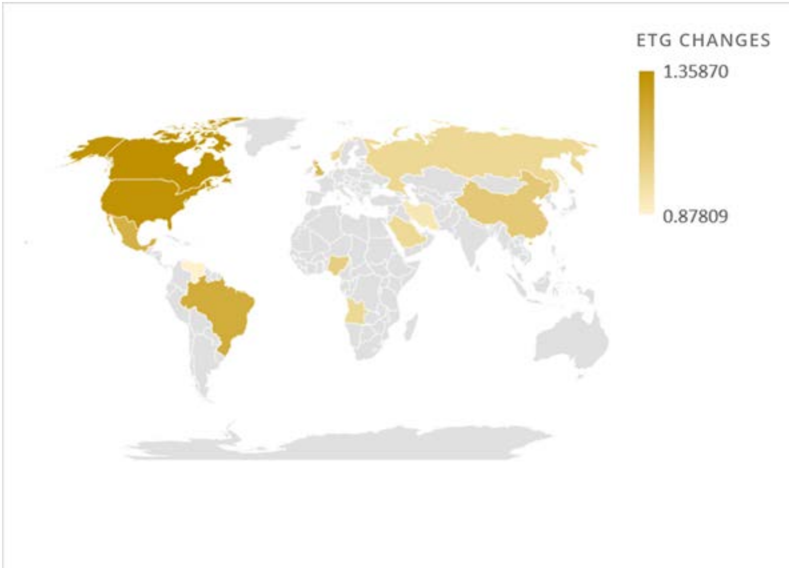
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A6. *SE Changes Geographic Distribution (Averages)*



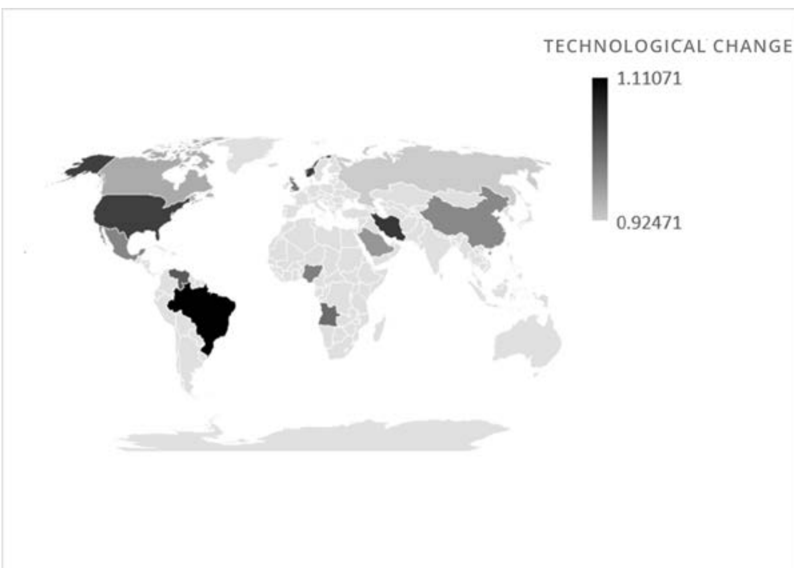
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A7. *OTE Changes Geographic Distribution (Averages)*



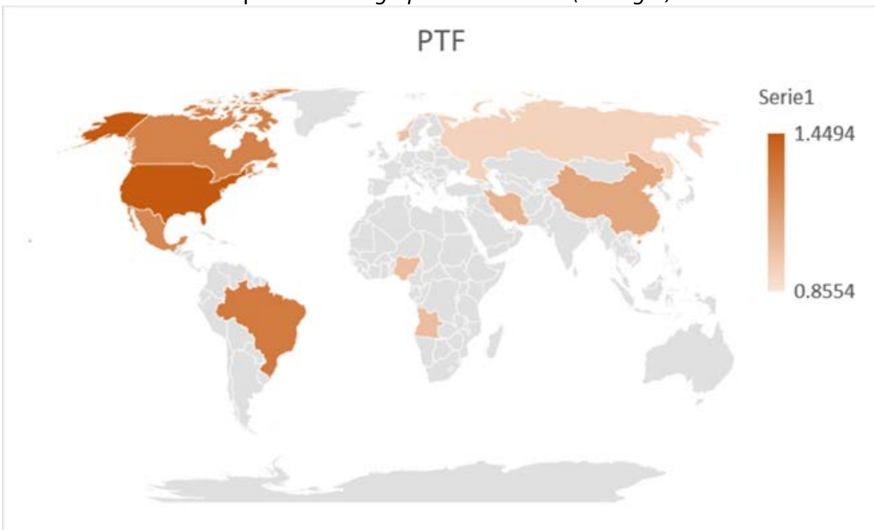
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A8. *TC Geographic Distribution (Averages)*



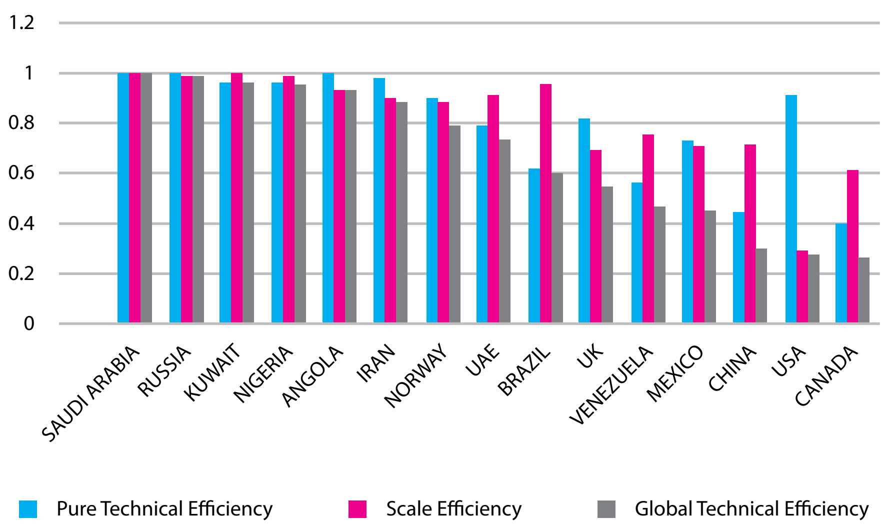
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Map A9. *TFP Geographic Distribution (Averages)*



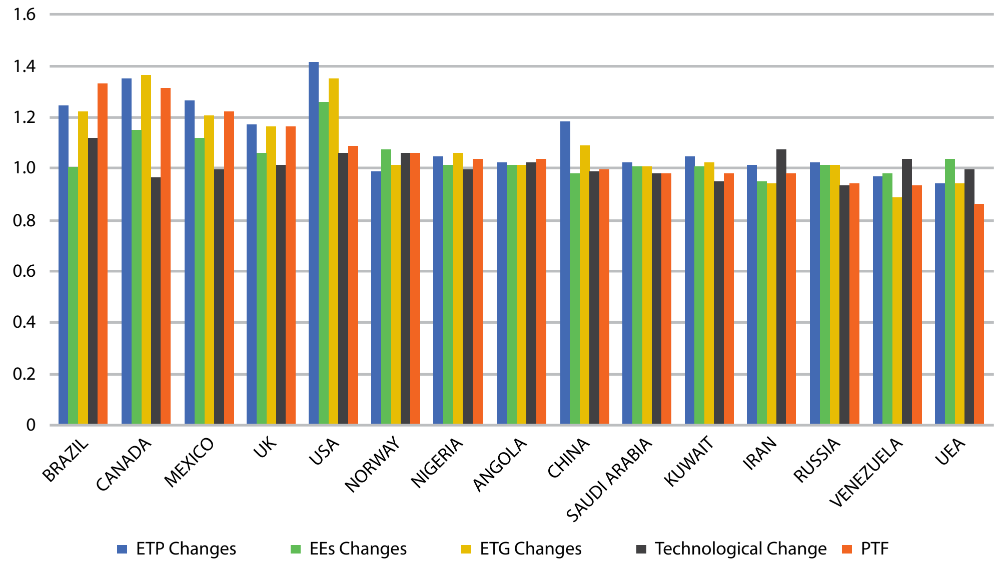
Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Graph 15. *OTE Components (Averages)*



Source: Authors' design based on calculations made in RStudio, GeoNames application (2019).

Graph 16. *TFP Components (Averages)*



Source: Authors' design based on calculations made in RStudio (2019).

Glossary

Allocative Efficiency. Producing a given quantity of goods using the minimum possible monetary expenditure on inputs according to their prices (Alé Yarad, 1990). It also considers the monetary value of the outputs, through which it seeks to maximize income.

Benchmarking. Benchmarking is defined as comparing a firm's performance with that of best-in-class companies. It determines how the best of them have achieved their performance levels: the information is used as a basis to set a company's own goals, strategies, and procedures (Bemowski, 1991).

Constant Returns to Scale. Production increases in the same proportion as the quantity of each of the factors is increased (Varian, 1998).

DEA. Non-parametric deterministic frontier model based on the quantities of inputs used and the quantities of outputs produced; it determines the best practices comparing a DMU with all the possible linear combinations of other units in a sample. Subsequently, it defines an empirical production frontier with them. Each DMU's efficiency is measured based on their distance from the frontier (Navarro, 2005).

Decreasing Returns to Scale. Production increases in smaller proportion than the increase of each factor (Varian, 1998).

Economic Efficiency. "Achievement of maximum production at the lowest possible cost" (Pinzón, 2003: 17).

Efficiency. Achievement of goals using the least number of resources (Giménez, 2004).

Fracking. It is the creation of fractures in the subsoil with pressurized water, with the aim of facilitating the extraction of hydrocarbons; it is also known as hydraulic fracturing (King, 2012).

Gross Fixed Capital Formation. Total value of acquisitions minus fixed assets used for production plus expenditures on services that increase the value of non-produced assets. The coverage of gross fixed capital formation should be precisely defined, so it is necessary to define what is and what is not a fixed asset as well as the activities that add value to non-produced assets (Baran, 1959).

Increasing Returns to Scale. Production increases in greater proportion than the increase of each factor (Varian, 1998).

Index Number. "A quantity that shows, by means of its variation, the changes over time or space of a quantity that is not itself susceptible to direct measurement or direct observation in practice" (Sumanth, 1990: 99).

Inputs. Refers to all goods needed for production (Kendrick, 1961).

Linear Programming. This is the field of mathematical optimization dedicated to maximizing or minimizing (optimizing) a linear function called the objective function; the variables of said function are subject to a series of restrictions expressed through a system of equations or inequalities that are also linear (Val-Arreola *et al.*, 2005).

Net Exports. They represent the difference between exports *(X)* and *(M)*. This is the difference between foreign income for local products and domestic spending for products made abroad (Economipedia, 2018).

Outputs. Goods resulting from a productive process; it is the good or service delivered to the market and the collateral and/or supplementary effects of the process (Kendrick, 1961).

PIDIREGAS. Investment scheme (exclusive to PEMEX and CFE) based on financing from private investors. The public sector begins to pay for this investment with budgetary resources once the projects are received to the satisfaction of the contracting entity (PEMEX, 2019).

Productivity. Ratio between the output obtained by a production or service system and the resources used to obtain it (Prokopenko, 1987).

Scale Efficiency. Shows whether a certain production unit has reached the optimal point of scale. It is only relevant when the production technology presents variable returns to scale *(idem).*

Slack Analysis. Sets the guidelines for DMU's to improve their efficiency levels. (Giménez, 2004).

Technical Efficiency. Consists of obtaining the maximum feasible physical production from a certain number of inputs given the existing technology *(idem).*

Total Factor Productivity (TFP). It is the ratio of net output to the sum of factor inputs such as labor, capital, and technical efficiency (Comin, 2010).

Variable Returns to Scale. It is the result of increasing the quantity of a variable factor to a fixed quantity of another factor; the physical product obtained varies differently from the increase of the variable factor (Martínez & Maza, 2003).

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Google Scholar: https://scholar.google.com/citations?user=S73n-M4YAAAAJ&hl=es

Index of Acronyms and Abbreviations

Art.	Article
CAPEX	Capital Exchange (Investment in capital assets)
CRS	Constant Returns to Scale
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
EE	Economic Efficiency
EP	Export and Production
GDP	Gross Domestic Product
IOC	International Oil Company
MXN	Mexican Peso
NOC	National Oil Company
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operational Exchange (Investment in operations)
OTE	Overall Technical Efficiency
PEMEX	Petróleos Mexicanos company
PIDIREGAS	Productive Infrastructure Investment Project with Deferred Registration in Public Expenditure
PTE	Pure Technical Efficiency
SE	Scale Efficiency
SEC	Securities and Exchange Commission
SENER	Mexico's Ministry of Energy
SNT	Mexico's National Transparency System

SPC	Subsidiary Productive Company
TC	Technological Change
TFP	Total Factor Productivity
UK	United Kingdom
USA	United States of America
USD	United States Dollars
VRS	Variable Returns to Scale

Index of Tables, Graphs, and Figures

Tables

Graphs

Figures

General Index

Global Oil Industry Efficiency and Productivity in the Upstream Sector. An Analysis Based on Non-Parametric Methods, 2008-2017, of Juan José Ortiz Villegas y Jorge Víctor Alcaraz Vera, published by Ediciones Comunicación Científica, S. A. de C. V., was completed in January 2024, Litográfica Ingramex, S. A. de C. V., Centeno 162-1, Granjas Esmeralda, 09810, Mexico City. The print run was 100 copies in print and in digital version in PDF, Epub and HTML formats.

The book addresses a crucial issue regarding the economic development of countries. The structure of the oil industry -and in particular the upstream sector, responsible for the exploration and extraction of hydrocarbons- maintains a strategic value, since a large part of the energy sovereignty of each region depends on it; the income it generates in the local and international markets affects the economic performance variables of companies and populations around the world.

In this scenario, the work presented is focused on diagnosing the efficient performance of the upstream sector of each economy and on finding out whether total factor productivity means that the economy has progressed technologically and has improved the efficiency in the use of its resources, thus achieving an increase in its production by improving the combination of its factors and its production processes.

This book is a valuable input for the design and implementation of a national public energy policy for the operations of the state-owned company Petróleos Mexicanos (Pemex), since it provides a tool to evaluate the role of efficiency and technological change in the productivity of the factors used, with the purpose of improving its processes and identifying the moments when it is reduced, thus being able to react in time to formulate more realistic objectives and determine the factors that contribute to improve it.

Juan José Ortiz Villegas is a PhD student in International Business Sciences at the Instituto de Investigaciones Económicas y Empresariales (ININEE) of the Universidad Michoacana de San Nicolás de Hidalgo (UMSNH). He is currently conducting research on sustainability, energy consumption, productivity and efficiency of the oil industry and the transition to clean energy at the Center for Social Research of the same institution..

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DOI.ORG/10.52501/CC.128

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ISBN-13: 978-607-59874-0-8

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